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# Evaluation of Full-Scale Tertiary Wastewater Filters

Northwestern Univ.
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16. ABSTRACT

Conventional methods for treatment of municipal wastewaters frequently produce effluents that will not meet local discharge requirements. Granular media filters are being installed to provide tertiary treatment for increased removals of suspended solids and BOD. This report provides performance data for full-scale tertiary filters from eight treatment plants and discusses effects of various design and operating practices. Semi-empirical mathematical models in the report relate filter clarification efficiency to characteristics of secondary effluent particulate matter and to filter operating parameters. The models developed in this study may be applied with some caution to predict filter suspended solids removal or clarification efficiency without pilot-scale tests.

An important design consideration for small scale tertiary wastewater filters was found to be the ability to handle shock loads caused by secondary process upsets. This consideration generally favors those designs with slow rate of headloss development. Clarification efficiency is only weakly dependent on filter media depth and media grain size. Better correlations of filter clarification efficiency have been obtained for grab compared to composite sample data. Composite process variables generally fit a log normal distribution best and normal distribution second best.

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# EVALUATION OF FULL-SCALE TERTIARY WASTEWATER FILTERS

by

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Conventional methods for treatment of municipal wastewaters frequently produce effluents that will not meet local discharge requirements. Granular media filters are being installed to provide tertiary treatment for increased removals of suspended solids and BOD. This report provides performance data for full-scale tertiary filters from eight treatment plants and discusses effects of various design and operating practices. Semi-empirical mathematical models in the report relate filter clarification efficiency to characteristics of secondary effluent particulate matter and to filter operating parameters.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

# ABSTRACT

The clarification efficiency of eight full scale tertiary granular media filters was characterized using conventional design and operating parameters, such as influent suspended solids and flow rate, and properties of secondary effluent suspensions (refiltration, particle size). Clarification efficiency is only weakly dependent on filter media depth and media grain size. Better correlations of filter clarification efficiency have been obtained for grab compared to composite sample data. Composite process variables generally fit a log normal distribution best and normal distribution second best.

Refiltration parameters were shown to have a very strong correlation with filter performance for plants where straining filtration was believed to be the dominant particle collection mode. Semiempirical mathematical models were developed to characterize "in-depth" and "straining" filtration. If in-depth filtration was the dominant particle collection mode, inclusion of refiltration parameters did not improve model prediction. The models developed in this study may be applied with some caution to predict filter suspended solids removal or clarification efficiency without pilot-scale tests.

An important design consideration for small scale tertiary wastewater filters was found to be the ability to handle shock loads caused by secondary process upsets. This consideration generally favors those designs with slow rate of headloss development.

This report was submitted in fulfillment of Grant Number R803212 by Northwestern University under the partial sponsorship of the Environmental Protection Agency. This report covers a period from November 9, 1974 - August 18, 1978 and work was completed as of August 1977.

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# LIST OF SYMBOLS

| | | |
|---|---|---|
| $C$ | -- Filter effluent suspended solids | $ML^{-3}$ |
| $C_o$ | -- Filter influent suspended solids | $ML^{-3}$ |
| $C/C_o$ | -- Ratio of effluent to influent suspended solids | |
| $C_b$ | -- Filter effluent BOD | $ML^{-3}$ |
| $C_{ob}$ | -- Filter influent BOD | $ML^{-3}$ |
| $C_oQ$ | -- Filter solids loading | $ML^{-2}T^{-1}$ |
| BOD | -- 5-day biochemical oxygen demand | $ML^{-3}$ |
| $d_e$ | -- Equivalent media diameter | L |
| $d_m$ | -- Media diameter | L |
| $d_{nm}$ | -- Number mean suspended particle | L |
| $d_p$ | -- Suspended particle size | L |
| $d_{10}$ | -- Effective media size | L |
| $d_{50}$ | -- Geometric mean media diameter | L |
| E | -- Refiltration parameter | $M^{1/6}L^{1/2}T^{-1/6}$ |
| G | -- Refiltration parameter | $LT^{-1/3}$ |
| $J_{N_O}$ | -- Particle flux to filter, particles/cm$^2$/sec | $L^{-2}T^{-1}$ |
| k | -- Parameter of negative binomial distribution | |
| L | -- Filter depth | L |
| $m_x$ | -- arithmetic mean | |
| $\breve{m}_x$ | -- geometric mean | |
| $N_{STR}$ | -- Dimensional straining parameter | $L^{-5}$ |
| Q | -- Superficial filtration rate | $LT^{-1}$ |
| r | -- Bivariate or multiple correlation coefficient | |
| $r_a$ | -- Autocorrelation coefficient | |
| $r_t$ | -- Multiple correlation coefficient for log transformation regression | |
| R | -- Refiltration parameter | M |
| RG | -- Refiltration parameter--product of R and G | $MLT^{-1/3}$ |
| RL | -- Run length | T |
| $S_c$ | -- lbs solids captured/ft$^2$ filter surface area/ft headloss buildup /ft bed depth | $M\ L^{-2}$ |
| $S_{ch}$ | -- lbs solids captured/ft$^2$ filter surface area/ft headloss buildup | $ML^{-1}$ |
| SS | -- Suspended solids | $ML^{-3}$ |
| t | -- Refiltration time | T |
| T | -- Temperature | °F |
| V | -- Volume of filtrate | $L^3$ |
| $VC_o$ | -- Weight of solids retained on filter paper in refiltration test | M |
| $x_{50}$ | -- Median value of distribution | |
| Z | -- Kolmogorov-Smirnov parameter (goodness of fit test) | |

LIST OF SYMBOLS (Continued)

Greek

| | | |
|---|---|---|
| $\alpha$ | -- Proportional to | |
| $\lambda$ | -- Filter coefficient | $L^{-1}$ |
| $\lambda_o$ | -- Initial filter coefficient | $L^{-1}$ |
| $\mu$ | -- Liquid viscosity -- centipoise | $ML^{-1}T^{-1}$ |
| $\sigma$ or $\sigma_x$ | -- Standard deviation | |
| $\sigma_{lnx}$ | -- Geometric standard deviation | |
| $\sigma_{nm}$ | -- Standard deviation of number mean particle size | L |
| $\sigma_s$ | -- Specific deposit--volume solids/volume filter | |
| $\chi^2$ | -- Chi square parameter (goodness of fit test) | |

Other

-- Parameters with $\overline{\phantom{x}}$ indicates arithmetic average, e.g. $\overline{Q}$, $\overline{C/C_o}$

Filtration Plant Codes

AN -- Addison North
AS -- Addison South (Filter No. 2)
AV -- Addison South (Filter Nos. 4,5,6,7)--variable flow studies
BA -- Barrington
DP -- Des Plaines River
LZ -- Lake Zurich
LI -- Lisle
MB -- Marionbrook
MBD -- Marionbrook--Dry weather flow, Phase 1
RO -- Romeoville
--L -- The third letter L, M, or H indicates a variable flow plant and low, medium or high flow rate
--2 -- A number following the code indicates the phase of the study

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# CHAPTER I

## INTRODUCTION

Filtration is considered to be the most important tertiary process in the implementation of the Federal Water Pollution Control Act Amendments of 1972 and 1977. Many existing secondary wastewater treatment plants cannot meet the minimum monthly average effluent standard of 30 mg/ℓ for suspended solids and biochemical oxygen demand (BOD) established by the Environmental Protection Agency in 1973. This is particularly true for small plants where removal efficiency is usually less than that achieved for large plants. The addition of tertiary filters will enable many plants to meet the standard and higher treatment levels for water quality limited streams. A survey conducted in 1974 by one of us (J.A.FitzPatrick) indicated only 77 operating U.S. tertiary filters treating secondary effluents greater than 0.3 mgd (Appendix D). Based on tertiary filtration needs reported by Lykins and Smith (1974) over 1,500 plants will be required to achieve water quality standards established by the 1972 Act. Approximately 94 percent of plants will be smaller than 5 million gallons per day (mgd) and 80 percent will be smaller than 1 mgd. An equivalent number of plants will be required in the future to meet the goals of the 1972 Act.

Research on tertiary wastewater filtration in the United States began in the mid-1960's. Since then numerous pilot-scale studies have been conducted to evaluate the effect of media size, media depth, and flow rate on process performance. It is generally recommended that pilot-scale studies be conducted to develop design parameters for full-scale plants since filtration models cannot be used to reliably predict performance (Cleasby and Baumann, 1974). The classical mechanisms for in-depth filtration, that were developed from studies of potable water filtration and from laboratory studies using suspensions with controlled properties, suggest a logarithmic removal of particles with depth, but do not adequately describe suspended solids removal for direct filtration of secondary effluents because greater than logarithmic removal of solids occurs due to straining at or near the surface of the filter medium. In addition, many of the models were developed with studies on unflocculated suspensions and describe only initial or clean bed filtration. In previous wastewater filtration studies, insufficient attention has been given to the effect of secondary effluent suspension properties on particle collection mode and clarification efficiency.

The objectives of this study have been to gain a clearer understanding of parameters affecting the clarification efficiency of full-scale granular media wastewater filters and to develop operational mathematical models to describe primarily this clarification efficiency. A four-phase study was conducted in the Chicago metropolitan area at eight plants with design flows of 0.8 to 2.5 mgd. At four plants the flow to three filters was varied from approximately 0.5 to 2 times average flow.

The objectives of Phase 1 were to characterize clarification efficiency as a function of conventional design and operating parameters and to determine the statistical properties of secondary effluent and filter effluent parameters. For this phase, all water quality data were obtained from flow-proportioned composite samples of secondary effluent and filter effluent. No routine tests were conducted on the properties of influent suspensions. Results of this phase are described in Chapters VII and VIII.

The results of Phases 2, 3 and 4 are given in Chapters IX and X. The objective of these phases was to refine prediction of performance by characterization of properties of filter influent suspensions. Phase 2 was conducted at the Addison South Plant where composite samples were obtained for refiltration tests. During Phase 3, grab samples were obtained at the Addison South and Des Plaines River Plants and particle size distributions were determined in addition to refiltration tests. Grab samples were obtained at all eight plants during the last phase and analyzed as in Phase 3.

Pertinent filtration literature is reviewed in Chapter VI to provide the basis for development of operational mathematical models to describe filter clarification efficiency.

# CHAPTER II

# CONCLUSIONS

This study of full-scale granular media filters consisted of four phases. In the first phase, filter clarification efficiency was characterized using conventional design and operating parameters, and the statistical properties of secondary effluent and filter effluent parameters were determined. In later phases, clarification efficiency was characterized using properties of secondary effluent suspensions (refiltration, particle size).

## Frequency Distributions of Secondary Effluent and Filter Effluent Parameters

1. Mean filter influent BOD ($C_{ob}$) varied from 9 to 44 mg/ℓ for the eight plants, and mean effluent BOD ($C_b$) varied from 3 to 25 mg/ℓ. The average ratio of effluent to influent BOD ($C_b/C_{ob}$) varied from 0.13 to 0.82. Filters cannot be compared directly for BOD removal efficiency because of the dissolved fraction that varies for the secondary treatment processes.

2. Average secondary influent suspended solids varied from 28 to 62 mg/ℓ and filter effluent suspended solids from 5 to 20 mg/ℓ. Coefficient of variation for influent suspended solids ranged from .33 to .60 while for effluent suspended solids the range was .25 to .80, indicating a wider range in effluent than influent characteristics during the sampling periods. The average ratio of effluent to influent suspended solids ($\overline{C/C_o}$) varied from 0.17 to 0.53 for the eight plants.

3. The majority of the data obtained in this study appears to fit a log normal distribution but occasionally a better fit to the normal distribution was obtained.

4. Extreme values of the data are generally not well predicted by either the normal or the log normal distributions. Truncated or censored distributions may give a better fit. Alternatively larger data sets may be required to give more stable frequency plots.

5. Visual fitting of effluent quality data on probability plots generally corroborates quantitative goodness of fit tests but still may be misleading, particularly regarding extreme value prediction.

6. There is an indication that some of the parameters have bimodal distributions. Over longer periods of time these might become multimodal and

with enough data the total distribution may still go over to a log normal distribution.

7. The extent of autocorrelation of the data was low enough so that the basic assumption that the data are independent was reasonable.

## Design Considerations

1. The most important single design consideration for small tertiary filtration plants is the ability to handle secondary process upsets. This consideration favors all filters evaluated except the Environmental Elements design.

2. Emergency overflows are needed for backwash equalization basins.

3. Gravity backwashing is not complete for dual media filters and results in 25 to 50% washable solids in the solids inventory. No apparent deterioration in performance occurs because of the high solids inventory.

4. In the absence of control system malfunctions, media loss is normally 5 to 10% per year for the dual media designs.

5. Mudball formation or filter bed cracking has never been observed in the dual media filters evaluated in this study.

## Characterization of Clarification Efficiency Using Conventional Design and Operating Parameters

1. For plants where flow to individual filters was varied, average clarification efficiency decreased linearly with average flow rate.

2. Correlation coefficients between filter solids removal efficiency and operating parameters such as flow, solids loading and run length are poor for data obtained over long time frames. Improved correlations were obtained for data analyzed over shorter time periods which minimized the effect of seasonal and other variations in secondary plant effluent suspension characteristics.

3. Differences in characteristics of secondary effluent suspended solids rather than media grain size and depth are most likely the major reason for variations in clarification efficiency between plants.

4. The following semiempirical model was developed for in-depth filtration:

$$C = 0.40\, C_o^{0.86} Q^{.34}$$

where: $C$ = filter effluent suspended solids - mg/ℓ

$C_o$ = secondary effluent suspended solids - mg/ℓ, and

$Q$ = filtration rate - gpm/sf

In testing with independent data, the in-depth model was able to predict

C within ± 25 percent for 85 percent of the data for three plants.

## Characterization of Clarification Efficiency Using Properties of Secondary Effluent Suspensions

1. Very poor simple correlations were obtained between refiltration parameters and particle size data.

2. Number mean particle size correlated with filter suspended solids removal efficiency within but not between plants.

3. Excellent simple correlations were obtained for filter suspended solids removal efficiency and the refiltration parameter E if straining was believed to be the dominant particle collection mode.

4. If in-depth filtration was believed to be the dominant particle collection mode, inclusion of E in semiempirical models did not significantly improve correlations.

5. Number mean particle size and E were generally smaller for plants where in-depth filtration was believed to be the dominant particle collection mode.

6. The following model developed from data from three plants can now be applied with caution for high values of E (>1.7):

   $$C = 4.24\, C_o^{1.40} Q^{.26} E^{-8.28}$$

7. A nearly perfect fit of the data was obtained in testing another model developed from the data for a plant where flow was varied to 3 filters with data from three other plants if only data with high values of E were included. For inclusion of all data, C was predicted within ± 30 percent for 80 percent of the data.

8. Both the straining and in-depth models tend to overpredict effluent suspended solids if the other particle collection mode apparently dominates.

# CHAPTER III

## RECOMMENDATIONS

Additional research on prediction of clarification efficiency of granular media filters is needed. The models developed in this study need to be tested with additional full-scale plant data. Research is needed on methods to determine a priori whether in-depth or straining filtration will be the dominant particle collection mode. The initial approach should include a pilot-scale study under controlled conditions.

## CHAPTER IV

## EXPERIMENTAL PROGRAM AND PROCEDURES

### PLANT DESCRIPTIONS

#### Secondary Plants

A summary of unit process data for the full scale secondary plants and filtration systems is given in Table 1. The Addison South and Lake Zurich plants have contact stabilization activated sludge and trickling filter processes in parallel. Other plants utilize contact stabilization activated sludge processes, with the exception of Marionbrook which also has one complete mix system. Aeration tank detention time based on raw sewage flow varies from about 6 to 10 hours and final sedimentation tank overflow rate from about 400 to 700 gpd/$ft^2$. These are considered to be typical design specifications for small-scale activated sludge plants.

Although only the Addison South and Barrington plants serve sewer systems that contain some combined sewers, large increases in flow occur for all plants during rains. Increases in plant flow also occur during the spring months when the ground water table is higher. This indicates that infiltration and inflow are severe problems. Many of the filtration process failures observed in this work occurred during rains when the final sedimentation tanks failed at high flows.

For the small plants in this study, the most troublesome unit operation is sludge processing and disposal. Except for anaerobic digestion for the Addison South and Lake Zurich trickling filter processes, and the Barrington plant, all plants utilize aerobic digestion. Frequent problems, such as equipment breakdowns, create a situation for the activated sludge plants where the only immediate solution is to increase the process solids inventory with a resulting reduction in removal efficiency of final clarifiers. There may also be a tendency for secondary process operation to be less precise since the operator knows that the filters will act as a "stop-gap."

#### Filtration Plant Designs

A summary of filtration plant design data is shown in Tables 2 and 3. Chemical treatment of secondary effluent prior to filtration, except for chlorination, was not practiced at any of the plants. Geometric mean media sizes ($d_{50}$) varied from 1.4 to 2.7 mm. for anthracite and 0.6 to 1.4 mm. for sand. Design depths ranged from 12 to 24 in. for anthracite and 10 to 24 in. for sand. Actual depths when sampling was conducted were consider-

Table 1. Unit process design data.

| Plant | Secondary Processes | | | | | | Filtration | |
|---|---|---|---|---|---|---|---|---|
| | No. of Units | Process(1) Type | Design Q-mgd | Contact Vol.$ft^3$ | Reaer.(2) Vol-$ft^3$ | Final Sed.(3) Area-$ft^2$ | No. of Units | Total Area-$ft^2$ |
| Addison North | 2 | CS | 2.0 | 33,000 | 85,000 | 3170 | 3 | 339 |
| Addison South | 2 | CS<br>TF | 1.2<br>0.9 | 13,000 | 40,000 | 1920 | 7 | 791 |
| Barrington | 2 | CS | 2.0 | 26,000 | 43,000 | 2710 | 4 | 464 |
| Des Plaines River | 2 | CS | 2.0 | 25,000 | 49,000 | 3200 | 2 | 1400 |
| Lake Zurich | 1 | CS<br>TF | 0.30<br>0.50 | 5,000 | 10,000 | 480 | 5 | 201 |
| Lisle | 3 | CS | 2.3 | 37,000 | 45,000 | 5320 | 6 | 678 |
| Marionbrook | 2<br>1 | CS<br>CM | 1.5<br>1.5 | 17,000<br>84,000 | 34,000<br>-- | 4110<br>3710 | 6 | 678 |
| Romeoville | 4 | CS | 2.0 | 36,000 | 72,000 | 3640 | 3 | 546 |

(1) Abbrev: CS - contact. stab. act.sludge, CM - complete mix act: sludge, TF - trickling filter.

(2) Reaeration tank volume.

(3) Final sedimentation tank area.

## Table 2. Filtration plant characteristics.

| Plant (1) | Secondary Process (2) | Secondary Design Flow in million gallons per day (3) | Filter Vendor(1) (4) | Flow rate in gallons per minute per square foot | | | Backwash | | | | Suspended Solids Removal Efficiency (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Actual | | | | | | | | |
| | | | | Design (5) | Mean(3) (6) | Coefficient of variation(4) (7) | Mode: head loss in feet or time in hours (8) | Wash rate in gallons per minute per square foot (9) | Volume in gallons per square foot (10) | Wash time in minutes (11) | Number of data (12) | Mean (13) | Coefficient of variation(4) (14) |
| Addison North | AS | 2.0 | S&L | 4.3 | 3.8 | 0.16 | 8 ft. (24 hr.) | 11.5- | 44 | 6 | 73 | 83 | 0.65 |
| Addison South<br>#1,2,3<br>#4,5,6,7 | AS & TF (1:1)(6) | 2.1 | S&L | 2.2 | 2.1<br>0.87<br>1.8<br>3.4 | 0.22<br>0.21<br>0.28<br>0.25 | 13 ft. | 15-9<br>17-7<br>17-7<br>17-7 | 40-45 | 4 | 70<br>61<br>51<br>64 | 74<br>76<br>70<br>60 | 0.46<br>0.63<br>0.53<br>0.38 |
| Barrington | AS | 3.0 | Nep. Micro. | 2.0 | 3.6 | 0.23 | head-loss | | | | 58 | 68 | 0.34 |
| Lake Zurich | AS & TF (1:2) | 0.8 | Gen. Filt. | 2.5 | 1.3<br>2.3<br>3.9 | --(2)<br>--<br>-- | 8 ft. (24 hr.) | 7-3.5 | 31 | 10-13 | 24<br>48<br>22 | 66<br>52<br>47 | 0.26<br>0.33<br>0.21 |
| Lisle | AS | 2.5 | EIMCO | 2.6 | 1.4<br>3.0<br>5.3 | 0.26<br>0.26<br>0.17 | 8 ft. (24 hr.) | 18-10 | 45 | 5 | 32<br>29<br>35 | 82<br>76<br>66 | 0.50<br>0.54<br>0.59 |
| Marionbrook | AS | 2.5 | EIMCO | 2.5 | 1.2<br>2.4<br>4.4 | 0.36<br>0.31<br>0.36 | 8 ft. (24 hr.) | 13-10 | 45 | 5 | 105<br>100<br>55 | 80<br>74<br>73 | 0.65<br>0.65<br>0.67 |
| Des Plaines River | AS | 2.0 | Envir. Elem. | 1.0 | 0.76 | 0.39 | | | | | 60 | 79 | 0.34 |
| Romeoville | AS | 2.0 | Hydro Clear | 2.5 | 1.5 | 0.26 | | | | | 36 | 74 | 0.38 |

(1) Abbreviations: S&L and Loveless; Nep. Micro. - Neptune Microfloc; Gen. Filt. - General Filter, Envir. Elem. - Environmental Elements

(2) Filter operate at constant flow with on-off influent pump cycles.

(3) Arithmetic mean.

(4) Coefficient of Variation = standard deviation/arithmetic mean.

(5) Variation from beginning to end of cycle.

(6) Ratio of flow from activated sludge to trickling filter process. Performance data at 2.1 gpm/sf is for Filter #2. Other data are for Filter #4, 5, 6, 7.

Table 3. Filtration plant media specifications.

| Plant | Anthracite | | | | | | Sand | | | | | | $\frac{d_{90}\text{ anthracite}}{d_{10}\text{ sand}}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $d_{10}$ in milli | $d_{50}$ in milli-meters | $d_{90}$ in milli-meters | Uniformity Coefficient$^{(1)}$ | Depth in Inches | | $d_{10}$ in milli-meters | $d_{50}$ in milli-meters | $d_{90}$ in milli-meters | Uniformity Coefficient$^{(1)}$ | Depth in Inches | | |
| | | | | | Design | Actual$^{(3)}$ | | | | | Design | Actual$^{(3)}$ | |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) |
| Addison North | 1.8 | 2.7 | 3.8 | 1.61 | 24 | 21 | 0.86 | 1.4 | 2.2 | 1.80 | 24 | 24 | 4.4 |
| Addison South | | | | | | | | | | | | | |
| #1, 2, 3 | 1.2 | 1.7 | 2.2 | 1.53 | 24 | 9 | 0.51 | 0.67 | 0.88 | 1.41 | 24 | 22 | 4.3 |
| #4, 5, 6, 7 | 1.8 | 2.7 | 3.8 | 1.61 | 24 | 15 | 0.86 | 1.4 | 2.2 | 1.80 | 24 | 23 | 4.4 |
| Barrington$^{(2)}$ | 1.3 | 1.7 | 2.4 | 1.44 | 16 | 10 | 0.48 | 0.63 | 0.92 | 1.38 | 14 | 3$^{(2)}$ | 5.0 |
| Lake Zurich | | 1.4 | | | 12 | 1 | 0.42 | 0.71 | 0.98 | 1.81 | 12 | 11 | 5.1 |
| Lisle | 1.2 | 1.7 | 2.3 | 1.58 | 24 | 9-16$^{(4)}$ | 0.40 | 0.58 | 0.82 | 1.63 | 12 | 3 | 5.0 |
| Marion Brook | 1.2 | 1.6 | 2.2 | 1.48 | 24 | 4-13$^{(4)}$ | 0.46 | 0.66 | 0.86 | 1.52 | 12 | 10-11$^{(4)}$ | 4.7 |
| Des Plaines River | | | | | | | 0.70 | 0.96 | 1.2 | 1.46 | 11 | 11 | |
| Romeoville | | | | | | | 0.46 | 0.72 | 0.90 | 1.65 | 10 | 10 | |

(1) Uniformity coefficient = $d_{60}/d_{10}$

(2) Tri-media, 30 in. total, anthracite, garnet and silica sand.

(3) Estimated depth when sampling was conducted.

(4) Variation between individual filters.

(5) Filters #1, 2, 3 were constructed in 1969, and #4, 5, 6, 7 in 1973.

ably less for many plants because of media loss during backwashing since the plant was constructed or the media last replaced.

Six plants have filter configurations shown in Figure 1 with a backwash storage tank located above the sand and anthracite filter media, and a flow-splitter box for proportioning flow to individual filters (Smith and Loveless, General Filter, and Eimco designs). Adjustments were made to weir lengths in the splitter boxes for the Addison South, Lake Zurich, Lisle, and Marionbrook plants to vary the flow from approximately 0.5 to 2 times average for three filters.

During the filtration cycle, valves A and C in Figure 1 are open and valve B is closed. The level of liquid in the vertical influent pipe above the backwash storage tank level provides the head for filter operation. Secondary effluent flows through the filter media, into the underdrain system, and then to the backwash storage tank where it discharges over a horizontal weir. A sensor automatically initiates the backwash cycle when the headloss reaches a preset level. Valve B then opens and valves A and C close. A valve on a drain line (not shown) opens to lower the water level above the filter media prior to air scour. After air scour is completed, valve C opens and the media is fluidized by flow from the storage tank. The backwash cycle is terminated by a level sensor in the tank when the water level reaches a preset point and valves then return to their original positions.

The Neptune Microfloc design at Barrington utilizes a tri-media of anthracite, garnet, and silica sand with a total design depth of 30 in. A conventional gravity filter configuration is used similar to the historic designs for potable water filters. A surface wash system consisting of a rotating arm within the filter media is utilized in lieu of air scour. A pumped backwash cycle is initiated when the headloss reaches a preset level.

The Des Plaines River plant utilizes a Hardinge filter supplied by Environmental Elements Corporation. This design is unique in that an 11 inch deep single medium sand filter is divided into 8 inch wide compartments formed by a series of partitions. The backwash mechanism is a motor driven carriage assembly that moves down the length of the filter and backwashes one compartment at a time. Backwash water is pumped and air scour is not utilized.

The installation at Romeoville is a 10 inch sand filter supplied by Hydro-Clear Corporation. This design has two unique features to prolong filter runs. When the liquid level reaches a preset point in a filter run, an "air-mix" system with diffusers located several inches above the filter medium is actuated and serves to keep solids in suspension. A "pulse-mix" system causes air to rise periodically through the filter medium to dislodge particles from the surface and redistribute solids in the bed. The "air-mix" system continues in operation during a pumped backwash cycle.

## Unique Features of Plants

The activated sludge and trickling filter process effluents at the Addison South plant are combined in a flow equalization basin ahead of the filters. Filters Nos. 1, 2 and 3 were constructed in 1969 and Nos. 4, 5, 6 and 7 in 1973. Each filtration system has its own elevated flow splitter box

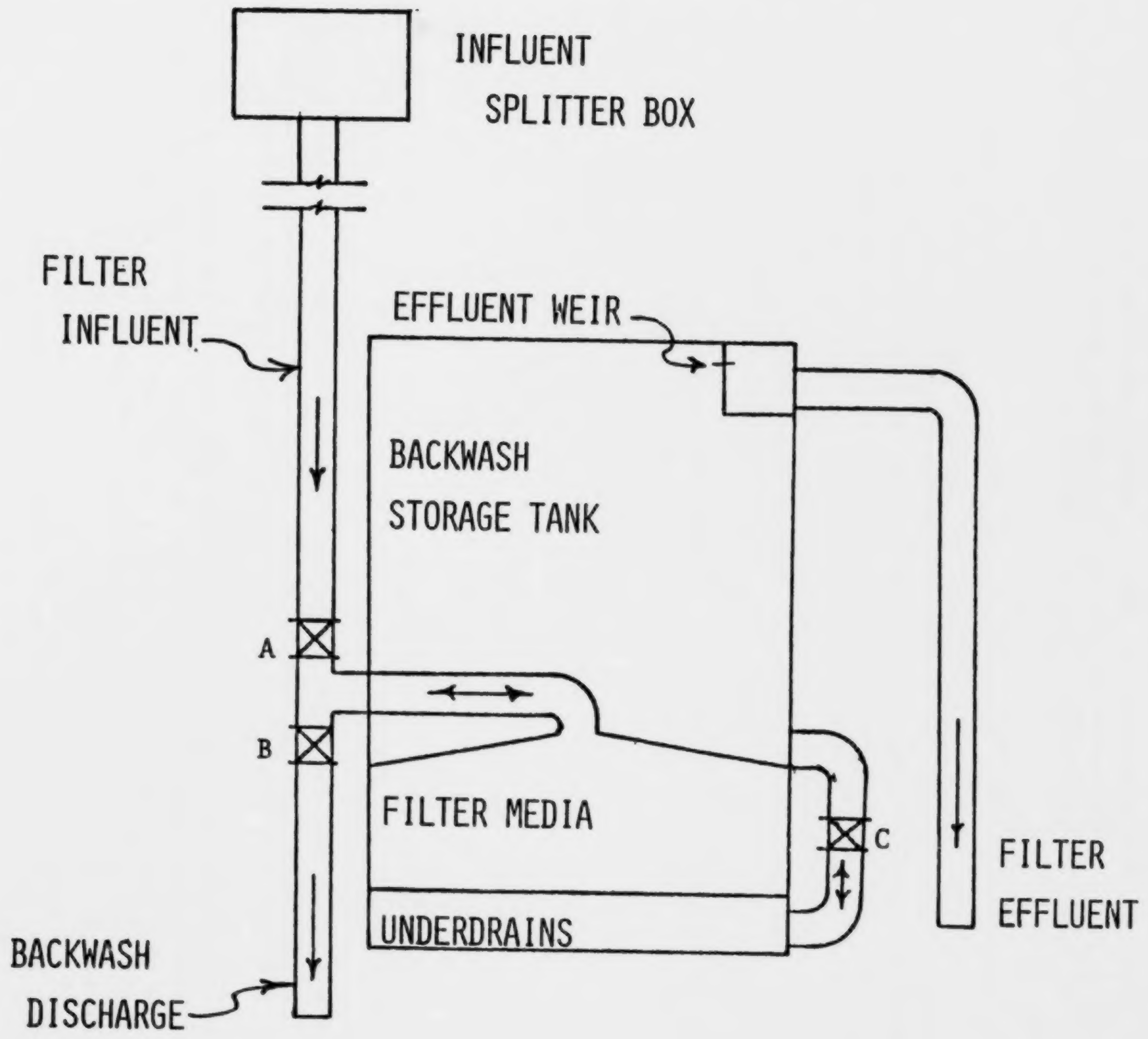

INFLUENT
SPLITTER BOX
FILTER
INFLUENT
EFFLUENT WEIR
BACKWASH
STORAGE TANK
A
B
FILTER MEDIA
C
FILTER
EFFLUENT
UNDERDRAINS
BACKWASH
DISCHARGE

Figure 1. Filter design.

which is connected to a common influent pump discharge header. The backwash cycle is initiated when the headloss reaches 13 feet for the Smith and Loveless filters. Springer (1975) conducted a study on the effect of flow surging on clarification efficiency during Phase 1. Springer found that by providing a larger wet well capacity, thus decreasing pump cycle frequency, he was able to improve average filter suspended solids removal efficiency about 10% (from 80 to 90%). Since the plants are served by a sewer system that has some combined sewers, raw sewage may be bypassed after chlorination during rains. The Addison North Plant has a basin that is used to store peak raw sewage flows for subsequent pumpback to the secondary plant. The basin serves as a primary sedimentation tank when the capacity is exceeded.

Barrington is the only plant that is manned 24 hours per day, seven days per week. All other plants are staffed for the day shift only and for a few hours on weekends and holidays.

At the Lake Zurich plant, the activated sludge and trickling filter process effluents are discharged to a lagoon ahead of the filters. The filter influent pumps are constant flow with on-off pump cycles. One large capacity pump operates during peak flows. During Phase 1 the filter media consisted of approximately 1 inch of anthracite intermixed with 11 in. of sand. The filter media was replaced with 12 in. of anthracite and 12 in. of sand prior to Phase 4.

The Lisle and Marionbrook plants have lagoons ahead of the filters. During Phase 1 at Marionbrook, the effluent from the contact stabilization plants was discharged to the lagoon. The effluent from the complete mix plant was discharged directly to the filters. During Phase 4 all plants discharged to the lagoon. The Eimco filter design at these plants has a timer mechanism that can be set to initiate the backwash cycle.

## PHASES OF STUDY

### Phase 1

In the initial phase of the study to characterize performance as a function of design and operational variables, all analyses were made on flow-proportioned composite samples of secondary effluent (filter influent) and filter effluent. Most sampling periods were 24 hours, with occasional periods of 4, 8, and 16 hours. Samples were analyzed for suspended solids and five-day BOD on a routine basis. Average run lengths were determined from backwash frequency counters or operating time for backwash mechanisms. For plants that did not have backwash frequency counters, mercury switches attached to valve operating mechanisms and clocks were used to determine frequency. Headloss at the end of runs was determined if filters were equipped with altitude gauges.

Sampling was conducted during the period from May, 1975, to August, 1976. Sampling programs were generally scheduled for two months at each plant to provide sufficient data for statistical analyses. Because filters were out of operation frequently, only 36 samples were obtained for the Romeoville plant. Fifty-eight or more samples were obtained for other plants. Flow rate was varied to three filters at the Addison South (Nos. 4-7), Lake Zurich, Lisle, and Marionbrook plants.

### Phase 2

Phase 2 was conducted at the Addison South plant in December, 1976, and January, 1977. Composite samples were obtained but were not proportioned according to flow. Flow was varied to three filters and Filter No. 2 was also sampled. Samples were analyzed for suspended solids only and refiltration tests were conducted.

### Phase 3

During Phase 3, conducted during March and April, 1977, grab samples were obtained at the Addison South (four filters) and Des Plaines River plants. Refiltration tests and particle size counts were made on-site. At Addison South, grab samples were obtained every half-hour and composited over a three-hour period. Samples were composited each hour at the Des Plaines River plant. Filter headloss data were obtained for both plants.

### Phase 4

Grab samples were obtained at all eight plants during Phase 4 in May and June, 1977. Suspended solids tests were conducted, as in Phases 2 and 3. Samples were transported to the laboratory for refiltration tests and particle size counts. Headloss measurements were made.

## SAMPLING EQUIPMENT AND FIELD PROCEDURES

### SERCO Samplers

Four SERCO automatic samplers (Model NW-3-DC), manufactured by Sonford Products Company, were used during Phase 1 along with flow splitter samplers described below. The SERCO sampler has 24 sample bottles with individual tubing connected to a metal sampler head, and a battery-operated trip arm. To set up the samplers, the sampler head is connected to a vacuum pump and bottles are vacated to about -25 in. Hg., and the tubing for each sample bottle is pinched off by a set switch. The movement of the trip arm can be adjusted to disengage a set switch at intervals from 2 min. to several hours. One sample per hour was obtained during Phase 1 and the units were not used during later phases.

### Flow Splitter Samplers

Several flow-proportioned sampling systems were designed and fabricated. The basic design consists of a "weir box", two cylinders with V-notch weirs on their peripheries connected in series, and a timer and solenoid.

The sampler device is attached to the weir and intercepts a relatively constant percentage of the total flow. Spacers were installed at the entrance to the weir box to obtain the desired flow rate. The effluent from the weir box is piped to the center of the first flow splitter. Flow from one V-notch is isolated and piped to the second flow splitter, where the flow from one V-notch is again isolated and piped to the timer-solenoid device. The final design utilized ten V-notch weirs on each cylinder for an approximate overall flow reduction of 1/100. The effluent line from the second flow splitter discharges to a plastic box and then to waste. The timer-solenoid device diverts the sample line for a few minutes per hour to an adjacent plastic box that is connected to a sample container.

A chronological summary of the sampling program and equipment used is given in Table 4.

## Sample Preservation

During May to August, 1975, ice was placed in a container inside of the SERCO samplers at the Addison North and South plants. The samplers were not housed at these plants. A timer-solenoid device was not used for the flow splitter samplers used for filter effluents and samples were collected in covered 50-gal. drums.

A decision was made to not preserve samples with ice for the remainder of the study because the major thrust of the study was on suspended solids removal, where changes in concentration would be expected to be less pronounced as compared to other parameters, and because of the additional field labor that would have been required.

## Flow Measurement

Each plant is equipped with indicating, recording, and totalizing raw sewage flow meters, except for the activated sludge portion of the Lake Zurich plant where flow is approximately one-third of total plant flow. Average plant flow during runs was determined from totalized flow readings. When the SERCO samplers were used, data from flow charts were used to flow proportion the composite samples, except at the Barrington plant where operators recorded the flow at two-hour intervals.

At Lake Zurich, where flow was varied to individual filters, rise rates in backwash storage tanks were measured and used to estimate flow (i.e., 1 ft/min. = 7.5 gpm/$ft^2$). Since the filter influent pumps operate at constant flow, a float-switch device was installed in the flow-splitter box and connected to a battery-operated clock to determine operating time during runs.

Rise rates in backwash storage tanks at the Addison South plant could not be used to estimate flow because of the flow equalization tank and on-off cycles for one large capacity influent pump. The flow to each filter was determined from measured total head on the effluent weirs using published graphs of head vs. discharge for weirs with end contractions. Measurements were made for a minimum of six days and the flow for each filter was totaled. Flows for all seven filters were totaled and the percentage of flow to each filter was calculated. These percentage factors were then applied to the metered plant flow to estimate average individual filter flow rates. Filters receiving the low, medium, and high flow rates were changed several times to minimize possible bias in the data. Each time a change was made, the above procedure was repeated.

Table 4. Chronological summary of sampling program and equipment used.

| Plant | No. of Data | Duration | Filter Influent Sampler(1) | Filter Influent Location(2) | Filter Effluent Sampler(1) | Filter Effluent Location(2) |
|---|---|---|---|---|---|---|
| Phase 1 | | | | | | |
| Addison North | 70 | 5-8/75 | S | O | F(3) | O |
| Addison South | 73 | 5-8/75 | S | O | F(3) | O |
| Barrington | 28 | 10-12/75 | S | I | S | O |
| Des Plaines R. | 45 | 10-12/75 | S | I | F | I |
| Lake Zurich | 94 | 10-12/75 | F | I | F | I |
| Marionbrook | 233 | 1-5/76 | F | I | F | I |
| Romeoville | 36 | 1-5/76 | S | I | S | I |
| Des Plaines R. | 14 | 4-5/76 | S | I | S | I |
| Barrington | 30 | 5-6/76 | S | I | S | O |
| Addison South | 176 | 5-7/76 | F | I | F | I |
| Lisle | 96 | 6-7/76 | F | I | F | I |
| Marionbrook | 27 | 7-8/76 | F | I | F | I |
| Phase 2 | | | | | | |
| Addison South | | 12/76-1/77 | F | I | F | I |
| Filt. 2 | 9 | | | | | |
| Filt. 4-7 | 27 | | | | | |
| Phase 3 | | (grab samples taken at 30-minute intervals and composited) | | | | |
| Addison South | | 2-3/77 | | | | |
| Filt. 2 | 5 | | | | | |
| Filt. 4-7 | 27 | | | | | |
| Des Plaines R. | 19 | 3-4/77 | | | | |
| Phase 4 | | (grab samples taken) | | | | |
| All Plants | 66 | 5-6/77 | | | | |

(1) S- SERCO Sampler, F- Flowsplitter sampler
(2) O- Sampler outside, I-sampler inside building
(3) Timer-soenoid not used.

At the Marionbrook and Lisle plants, the flow to filters was estimated from the ratio of individual filter weir length to total weir length in the flow splitter box. At Marionbrook, a portion of the secondary effluent was bypassed when flow was high. Since the filter effluent weirs were not readily accessible, a manometer was installed to measure the head in the flow splitter box. The manometer readings were compared to readings when the filters were not bypassed to estimate flows. This approximate procedure was used for 26 runs.

## LABORATORY PROCEDURES

Laboratory and field data are not reported here. They are included in the 1978 Ph.D. dissertation entitled "Evaluation of Full-Scale Tertiary Wastewater Filters" by Charles L. Swanson. Copies may be obtained from University Microfilms, Ann Arbor, Michigan.

### Standard Laboratory Analyses

All laboratory analyses for BOD and suspended solids were conducted in accordance with Standard Methods for the Examination of Water and Wastewater (1971 Edition). Dechlorination procedures were used prior to the BOD test for several samples from the Marionbrook plant in Phase 1 when chlorine residual was 0.2 to 0.4 mg/ℓ. It was found that the differences in BOD were within the standard error of measurement and dechlorination procedures were discontinued.

### Suspension Properties

Methods used to characterize secondary effluent suspensions were suspended solids concentration, refiltration parameters, and particle size measurements.

Hsiung (1972) was the first to utilize refiltration techniques to characterize performance of tertiary wastewater filters. The refiltration technique was first developed utilizing the Kozeny-Carmen equation by LaMer and Smellie (1956). This technique involves filtration of three or more samples with different volumes through microporous filter paper and measurement of the time for refiltration of the filtrate. When $VC_o$ is plotted vs $(V/t)^{1/3}$, a linear relationship is obtained, where

$V$ = volume of filtrate - mℓ,

$C_o$ = filter influent suspended solids - mg/ℓ, and

$t$ = refiltration time - sec.

Hsuing defined the refiltration parameters R and G as the intercepts on the ordinate and abscissa axes, respectively. He proposed an empirical factor, $E = (R^{1/3}G)^{1/2}$, and obtained data for pilot filtration of secondary effluents from 4 plants at a constant rate of 5 gpm/sf. An excellent correlation of E with percentage removal of suspended solids was obtained. In Chapter VI it is shown that for unisized particles, E is proportional to the cube root of the particle diameter. In this study an excellent correlation of $C/C_o$ with E was obtained for data sets where straining was believed to be the dominant particle collection mode.

Particle size counts were made using a compound microscope (100x) and a Porton graticule. The number mean particle diameter ($d_{nm}$) varied from 8 to 38 μm. Some correlation was obtained for $C/C_o$ vs $d_{nm}$ for individual plant data with particle collection efficiency increasing with larger particle sizes as would be expected. However, the particle number mean did not correlate well with $C/C_o$ between plants.

## Refiltration Tests

Refiltration tests were conducted using 0.45 μm Millipore filter paper (47 mm. diameter) and a standard Millipore Filtration Apparatus at a vacuum of 25 in.Hg. The procedure used by Hsiung (1972) for determining the refiltration parameters R (intercept on ordinate axis) and G (intercept on abscissa) was modified to account for differences in volume and temperature between the filtered sample and filtrate. The correction applied was:

$$t_c = t\frac{\mu_s V_s}{\mu_f V_f} , \qquad (1)$$

where $t$ = refiltration time--sec.,

$t_c$ = corrected time--sec.,

$V_s$ = volume of sample filtered--mℓ,

$V_f$ = volume of filtrate--mℓ,

$\mu_s$ = viscosity of sample-centipoise, and

$\mu_f$ = viscosity of filtrate-centipoise.

Viscosities were determined from sample and filtrate temperatures using Hazen's approximation (Fair, Geyer and Okun, 1968):

$$\mu_T = 78.6/(T + 10) \qquad (2)$$

where T is in $^{\circ}$F.

During Phase 2, at least four refiltrations were made for each sample in order to improve accuracy. Frequently, three points fell in a straight line with one outlying point. In those cases, the outlying point was excluded in estimating the line of best fit by eye. The filter paper was not prewashed with demineralized water during Phases 2 and 3.

During Phases 3 and 4, plots of $VC_o$ vs. $(V/t)^{1/3}$ were prepared during the tests and additional filtrations were made if a reasonable straight line fit was not obtained for three samples. The line of best fit was then determined using regression techniques on all data points.

Filter paper was prewashed with 100 mℓ of demineralized water during Phase 4. During this phase, filtrate from the suspended solids tests (glass fiber filters) for each plant was used for refiltration in order to streamline the test procedure. Before adopting this procedure, tests were conducted to compare results with use of filtrate from the Millipore filter paper. No significant differences (less than 1 or 2 percent at 2 min.) in refiltration time were obtained.

The accuracy of the refiltration test in determining the parameter E was estimated in Phase 4. Four filtrations were used for 21 of the 38 samples in this phase. In order to eliminate bias, these 21 samples were used for the following analysis. The assumption was made that the true value of E was that obtained for the regression of $VC_o$ vs. $(V/t)^{1/3}$ with the four data points. Four additional regressions were made for three data points with a different data point excluded each time. The method used to estimate error bounds is illustrated below for a sample obtained at the Barrington Plant (5/26/77).

| | E | Error--% |
|---|---|---|
| Four data | 1.403 | -- |
| Three data -- Run 1 | 1.418 | + 1.1 |
| -- Run 2 | 1.411 | + 0.6 |
| -- Run 3 | 1.404 | + 0.1 |
| -- Run 4 | 1.374 | - 2.1 |
| Error Range | | 3.2 |
| Error Bounds | | ± 1.6 |

One refiltration test had error bounds of ± 18 percent. For the remaining 20 samples, the error bounds ranged from ± 0.4 percent to ± 5.4 percent, with an average of ± 1.8 percent. A plot of $VC_o$ vs. $(V/t)^{1/3}$ is shown in Figure 2 for the Barrington plant sample, and the samples with error bounds of ± 0.4 and ± 5.4 percent. For the data in this analysis, it can be concluded that E is determined with an average accuracy of less than ± 2 percent for 95 percent of the samples.

## Particle Size Determinations

Wet mount particle size counts were made using a compound microscope (100 X) and a Porton graticule, shown in Figure 3. The graticule has circles with diameters increasing by a factor of $\sqrt{2}$. The diameters vary from approximately 4.2 μm for class 1 to 68 μm for class 9. Grids are used for particles larger than class 9. The lower one-half of the graticule, with an area of $10^{-3}$ $cm^2$ was used as the counting field. A counting cell with a depth of 1 mm. was used giving a viewing field volume of $10^{-4}$ $cm^3$.

Sample bottles were shaken by hand to break up large floc particles that tended to form during the time from collection and during transport to the laboratory. Samples were placed in the counting cell using a wide tipped 10 mℓ pipette.

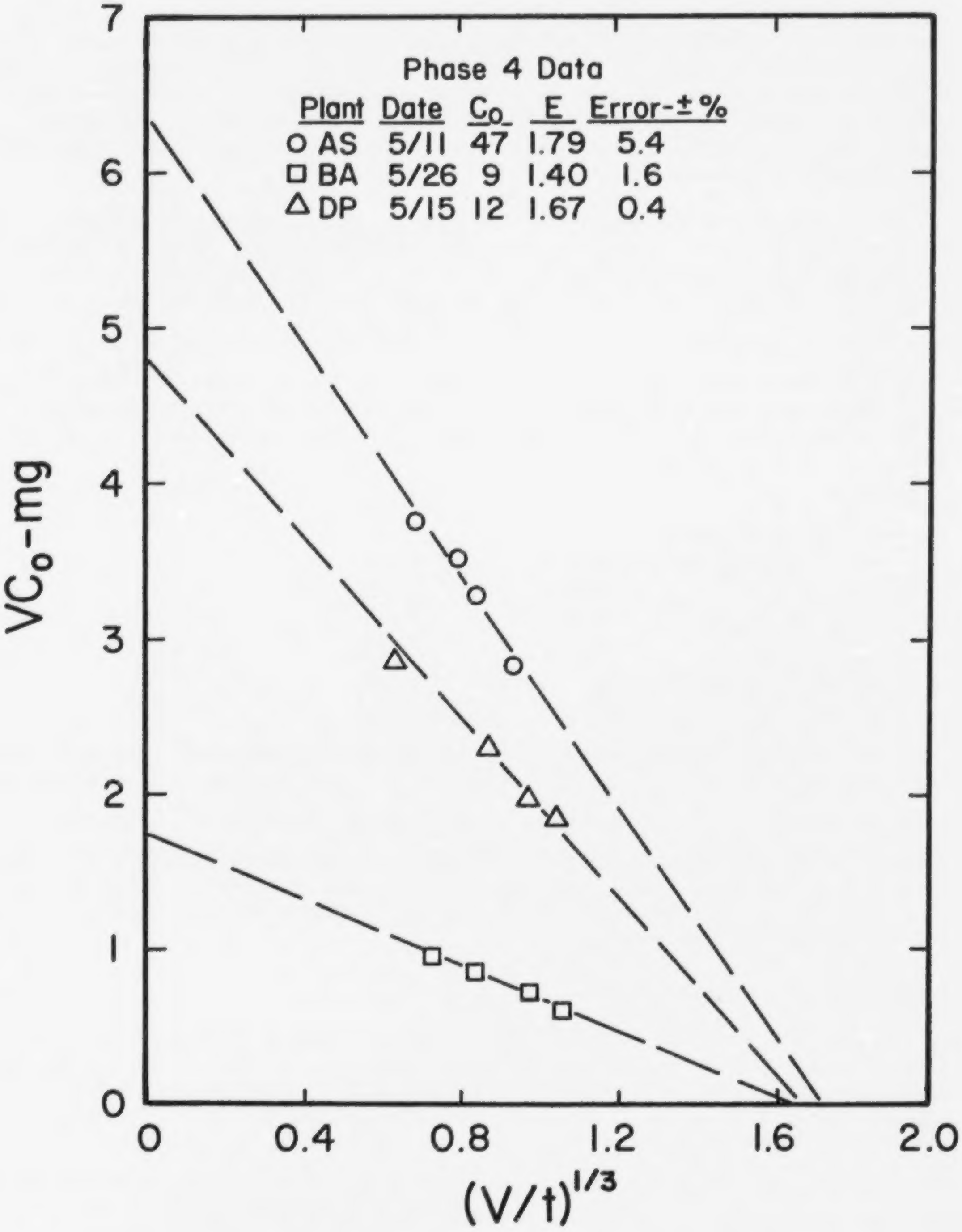


Figure 2. Refiltration data plot, V $C_o$ vs. $(V/t)^{1/3}$.

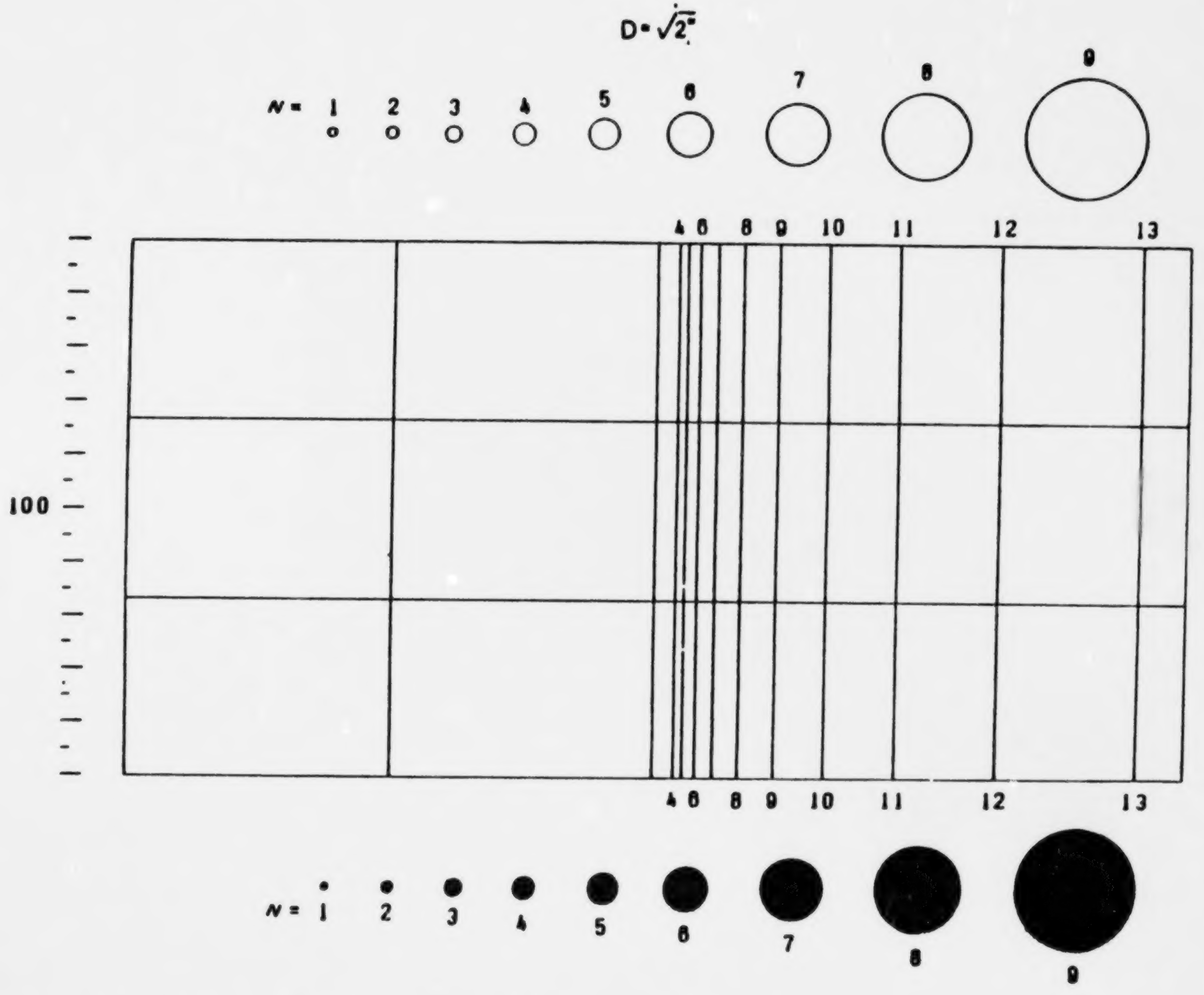

$D = \sqrt{2^N}$
N = 1 2 3 4 5 6 7 8 9
4 6 8 9 10 11 12 13
100
4 6 8 9 10 11 12 13
N = 1 2 3 4 5 6 7 8 9

Figure 3. Drawing of porton graticule (magnification 280X).

The number of fields used to determine the particle counts in each size class varied from 6 to 40, depending on the particle concentration. In order to eliminate bias in the analysis, the counting cell was moved while the field was not viewed. The standard method of viewing enough fields to count a specified minimum number of particles in the largest size class was not used because of the excessive time requirements for dilute samples.

## CHAPTER V

## PERFORMANCE DATA AND OBSERVATIONS OF PLANT OPERATIONS

### REMOVAL OF BOD AND SUSPENDED SOLIDS

Tertiary granular media filters are designed primarily for removal of suspended solids and the BOD associated with the suspended solids. However, removal of dissolved BOD occurs to some extent due to bacterial activity within the filter media. Dissolved BOD is defined here as that BOD associated with the filtrate from a standard glass fiber filter. Some colloidal solids measured in that filtrate may be transported to the full-scale filter medium by Brownian diffusion (Cookson, 1970) and removed or metabolized by attached microbial populations.

A summary of BOD removal data is shown in Table 5. Mean filter influent BOD ($C_{ob}$) varied from 9 to 44 mg/$\ell$ for the eight plants, and mean effluent BOD ($C_b$) varied from 3 to 25 mg/$\ell$. The average ratio of effluent to influent BOD ($C_b/C_{ob}$) varied from 0.13 to 0.82. Filters cannot be compared directly for BOD removal efficiency because of the dissolved fraction that varies for the secondary treatment processes.

Dissolved BOD tests were conducted for a portion of the sampling program at the Addison North and South plants and were not made routinely thereafter. Plots of effluent vs. influent dissolved BOD are shown in Figure 4. It is apparent that a significant removal of dissolved BOD occurs for these filters. Average influent and effluent dissolved BOD is shown below.

| | Addison North | Addison South |
|---|---|---|
| Dissolved $C_{ob}$ --mg/$\ell$ | 7.5 | 8.6 |
| Dissolved $C_b$ --mg/$\ell$ | 3.8 | 6.0 |
| % Removed | 49 | 30 |

This observed removal also probably reflects the fact that biofilms attached to the filter media serve as adsorption sites for some components of the noncolloidal organics. Dissolved oxygen levels in filter influents are high due to turbulence in the flow splitter boxes and filter influent lines, providing sufficient oxygen for aerobic bacterial activity.

A summary of average flow and suspended solids data is shown in Table 6.

Table 5. Statistics for BOD data - Phase 1.

| Plant | No. of Cases |  | Effluent $C_b$-mg/l |  |  | Influent $C_{ob}$-mg/l |  |  | $C_b/C_{ob}$ |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|
|  | $C_b$ | $C_{ob}$ | Mean | $\sigma$ | Range | Mean | $\sigma$ | Range | Mean | $\sigma$ | Range |
| Non-Variable Flow |  |  |  |  |  |  |  |  |  |  |  |
| Addison North | 54 | 61 | 5.1 | 4.0 | 1-18 | 34 | 12.6 | 11-69 | .13 | .10 | .01-.57 |
| Addison South (76) | 60 | 60 | 9.7 | 4.9 | 2-25 | 42 | 17.1 | 8-75 | .25 | .12 | .06-.64 |
| Barrington | 52 | 53 | 16 | 5.9 | 6-45 | 37 | 13.0 | 10-70 | .48 | .16 | .20-.84 |
| Des Plaines River | 55 | 56 | 3.3 | 3.6 | 1-23 | 34 | 21 | 5-90 | .13 | .14 | .03-.71 |
| Romeoville | 34 | 34 | 13 | 4.2 | 1-22 | 39 | 21 | 10-108 | .39 | .16 | .02-.76 |
| Variable Flow |  |  |  |  |  |  |  |  |  |  |  |
| Addison South-High Q | 14 | 18 | 25 | 5.7 | 17-35 | 44 | 13 | 22-70 | .64 | .17 | .42-1.0 |
| Lake Zurich- Med Q | 30 | 30 | 16 | 3.9 | 10-23 | 23 | 12 | 10-74 | .82 | .35 | .34->1 |
| Lisle - Med Q | 6 | 8 | 11 | 5.4 | 2-19 | 24 | 14 | 10-48 | .50 | .36 | .14-1.0 |
| Marionbrook- Low Q | 18 | 18 | 3.7 | 3.6 | 1-13 | 9.2 | 8.7 | 1-29 | .47 | .43 | .16-.85 |
| Marionbrook- Med Q | 16 | 16 | 3.2 | 2.3 | 1-10 | 9.9 | 5.5 | 5-21 | .34 | .15 | .16-.70 |

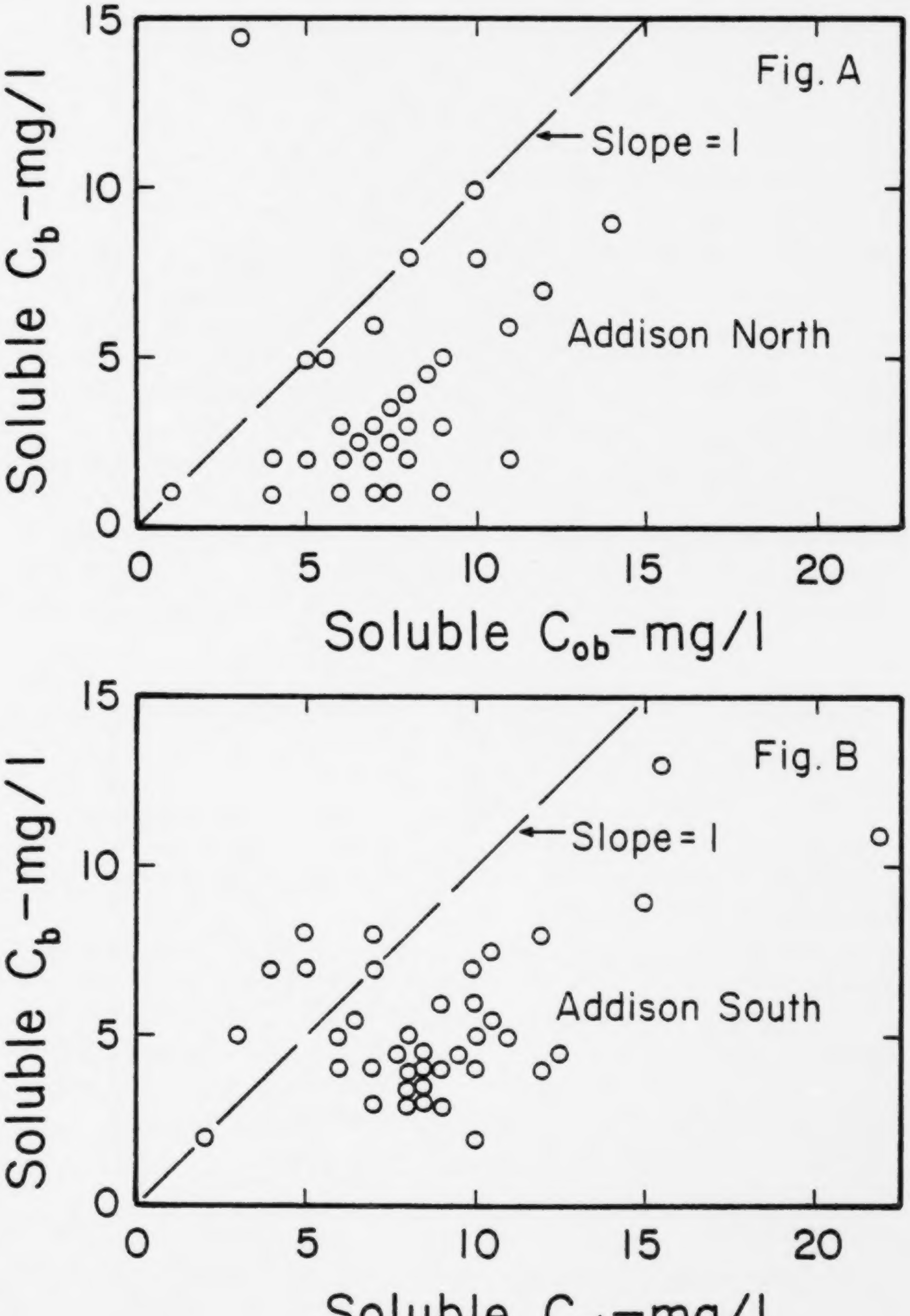


Figure 4. Filter effluent vs. influent soluble BOD, Addison North and South - Phase 1.

Table 6. Summary of plant performance data.

| Plant | No. of Data | Flow-gpm/sf | | Suspended Solids-mg/ℓ | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Influent($C_o$) | | Effluent(C) | | $C/C_o$ | |
| | | Mean(3) | CV(4) | Mean | CV(4) | Mean | CV | Mean | CV |
| Addison North | 73 | 3.8 | 0.16 | 44 | 0.43 | 6.6 | 0.56 | 0.17 | 0.65 |
| Addison S. (#2)(1) | 70 | 2.1 | 0.22 | 38 | 0.45 | 9.0 | 0.43 | 0.26 | 0.46 |
| Addison S. (#4-#7)(1) | | | | | | | | | |
| Low Flow | 61 | 0.87 | 0.21 | 52 | 0.42 | 11 | 0.65 | 0.24 | 0.63 |
| Medium Flow | 51 | 1.8 | 0.28 | 49 | 0.43 | 14 | 0.57 | 0.30 | 0.53 |
| High Flow | 64 | 3.4 | 0.25 | 51 | 0.43 | 20 | 0.60 | 0.40 | 0.38 |
| Barrington | 58 | 3.6 | 0.23 | 37 | 0.32 | 12 | 0.34 | 0.32 | 0.34 |
| Des Plaines River | 60 | 0.76 | 0.39 | 31 | 0.61 | 5.0 | 0.60 | 0.21 | 0.76 |
| Lake Zurich (1)(2) | | | | | | | | | |
| Low Flow | 24 | 1.3 | -- | 28 | 0.39 | 9.5 | 0.31 | 0.34 | 0.26 |
| Medium Flow | 48 | 2.3 | -- | 31 | 0.35 | 14 | 0.31 | 0.48 | 0.33 |
| High Flow | 22 | 3.9 | -- | 29 | 0.38 | 15 | 0.25 | 0.53 | 0.21 |
| Lisle | | | | | | | | | |
| Low Flow | 32 | 1.4 | 0.26 | 62 | 0.61 | 9.0 | 0.51 | 0.18 | 0.50 |
| Medium Flow | 29 | 3.0 | 0.26 | 59 | 0.61 | 12 | 0.62 | 0.24 | 0.54 |
| High Flow | 35 | 5.3 | 0.17 | 61 | 0.61 | 18 | 0.72 | 0.34 | 0.59 |
| Marionbrook | | | | | | | | | |
| Low Flow | 105 | 1.2 | 0.36 | 38 | 0.53 | 7.1 | 0.76 | 0.20 | 0.65 |
| Medium Flow | 100 | 2.4 | 0.31 | 34 | 0.50 | 8.4 | 0.79 | 0.26 | 0.65 |
| High Flow | 55 | 4.4 | 0.36 | 32 | 0.59 | 7.2 | 0.64 | 0.27 | 0.67 |
| Romeoville | 36 | 1.5 | 0.26 | 31 | 0.55 | 7.4 | 0.50 | 0.26 | 0.38 |

(1) Secondary process - activated sludge and trickling filters in parallel. Other plants activated sludge.

(2) Filters operate at constant flow with on-off influent pump cycles.

(3) Arithmetic mean

(4) Coefficient of Variation = standard deviation/arithmetic mean

Average secondary influent suspended solids varied from 28 to 62 mg/ℓ and filter effluent suspended solids from 5 to 20 mg/ℓ. Coefficient of variation for influent suspended solids ranged from .33 to .60 while for effluent suspended solids the range was .25 to .80, indicating a wider range in effluent than influent characteristics during the sampling periods. The average ratio effluent to influent suspended solids ($C/C_o$) varied from 0.17 to 0.53 for the eight plants.

## DESIGN CONSIDERATIONS

### Process Selection

Historically, optimal design for potable water treatment has been defined as the condition where effluent turbidity breakthrough occurs at the time the terminal headloss is reached (Ives, 1972). This concept has also been extended to tertiary wastewater filtration, along with optimizing run length by determining the effect of recycled backwash on secondary treatment costs (Baumann and Huang, 1974).

In the authors' opinion, these concepts are not applicable to design of small-scale ( < 5 mgd) tertiary wastewater filters. As a practical matter, the incremental capital and pumping costs for changes in splitter box elevation over the normal design range for the filter configuration shown in Figure 1 are insignificant. In addition, the incremental secondary treatment costs for the additional capacity to handle backwash over the range of run lengths of 8 to 24 hours are not significant, particularly if one or two backwashes are set by timers to occur during diurnal periods when plant flow is low.

The most important single design consideration for small tertiary filtration plants that are not staffed 24 hours per day is the ability to handle secondary process upsets. This consideration appears to favor dual media designs with relatively large media and high terminal headloss since particle collection efficiency showed a weak dependence on media size, as discussed in Chapter VIII.

### Process Failures

Process failure of the Environmental Elements sand filter installation occurred at influent suspended solids concentrations of approximately 60 mg/ℓ. When failure occurred, the filter influent backed up and flowed into the backwash return channel, eventually overflowing into the filter effluent channel. At the time of sampling no automatic bypass was provided. In the subsequent plant expansion bypass occurs if the head on the filters exceeds 16 inches and is returned to the head of the plants.

The Hydro Clear design has a bypass weir to handle process upsets. Process failure for the Romeoville installation corresponds to exceeding the capacity of the backwash equalization basin ("mudwell"). This occurred under extended secondary process upsets because of a combination of unrelated drainage into the basin and inadequate basin drain pipe capacity. This design has an air pulse system and can handle considerably higher suspended solids levels than the Environmental Elements design if backwash basin capacity is adequate.

Multimedia designs with anthracite and sand $d_{50}$ of 1.4 - 1.7 mm and 0.58 - 0.71 mm respectively can generally function with influent suspended solids levels of approximately 80 to 100 mg/ℓ. No process failures were observed for the Barrington plant (Neptune Microfloc), which is staffed 24 hours per day. For this plant the filters are bypassed during secondary process upsets. Filter Nos. 4-7 at the Addison South Plant, with a $d_{50}$ of 2.7 mm for anthracite and 1.4 mm for sand, were able to filter influent suspended solids concentrations in excess of 200 mg/ℓ. It should be pointed out that under these conditions effluent suspended solids exceeded 30 and even 50 mg/ℓ and may still be unacceptable. Maximum available head is approximately 13 feet for the Smith and Loveless design, and 7 feet for the General Filter and Eimco designs. For the design shown in Figure 1 failure is considered to occur when the filter influent backs up into the flow splitter box.

In all 6 filter designs with an elevated splitter box, an overflow pipe is provided. The overflow piping system should be designed to handle the maximum capacity of the filter influent pumps. This is not the case at three plants where the splitter box overflows during secondary process upsets when the filters become clogged and backed up. The overflow drenches electrical and mechanical controls and causes malfunctions, in addition to flooding of the filter building. This also compounds the corrosion problem on electrical control mechanisms.

## Equalization of Backwash Water

Many state regulatory agencies require flow equalization facilities for return of backwash to the secondary treatment process in order to minimize flow surges. This requirement causes severe problems during secondary process upsets at three of the plants. At these plants, the equalization basins are located under the filters below grade level.

When filters backwash frequently, water backs up and floods the filter buildings. At one plant, doors on the filter building are left open to prevent submergence of automatic valve operating mechanisms. Depths in excess of 2 feet were observed in the filter building at one plant. This situation also occurs when valve control systems malfunction and backwash valves remain open. In this situation, secondary effluent discharges to the equalization basin and floods the building.

This problem could be eliminated by providing an overflow in the equalization basin to return backwash water directly to the secondary process. An alternative would be automatic shutdown of flow to the filters and bypassing directly to chlorination facilities, if permitted by regulatory agencies.

## Filter Media Backwashing

Backwash rate tests were conducted for all filtration plants with the backwash storage tank located above the filter media compartment. A plot of backwash flow rate vs cycle time for 3 filters is shown in Figure 5. For the large media at Addison South (No. 4) and Addison North the backwash rate

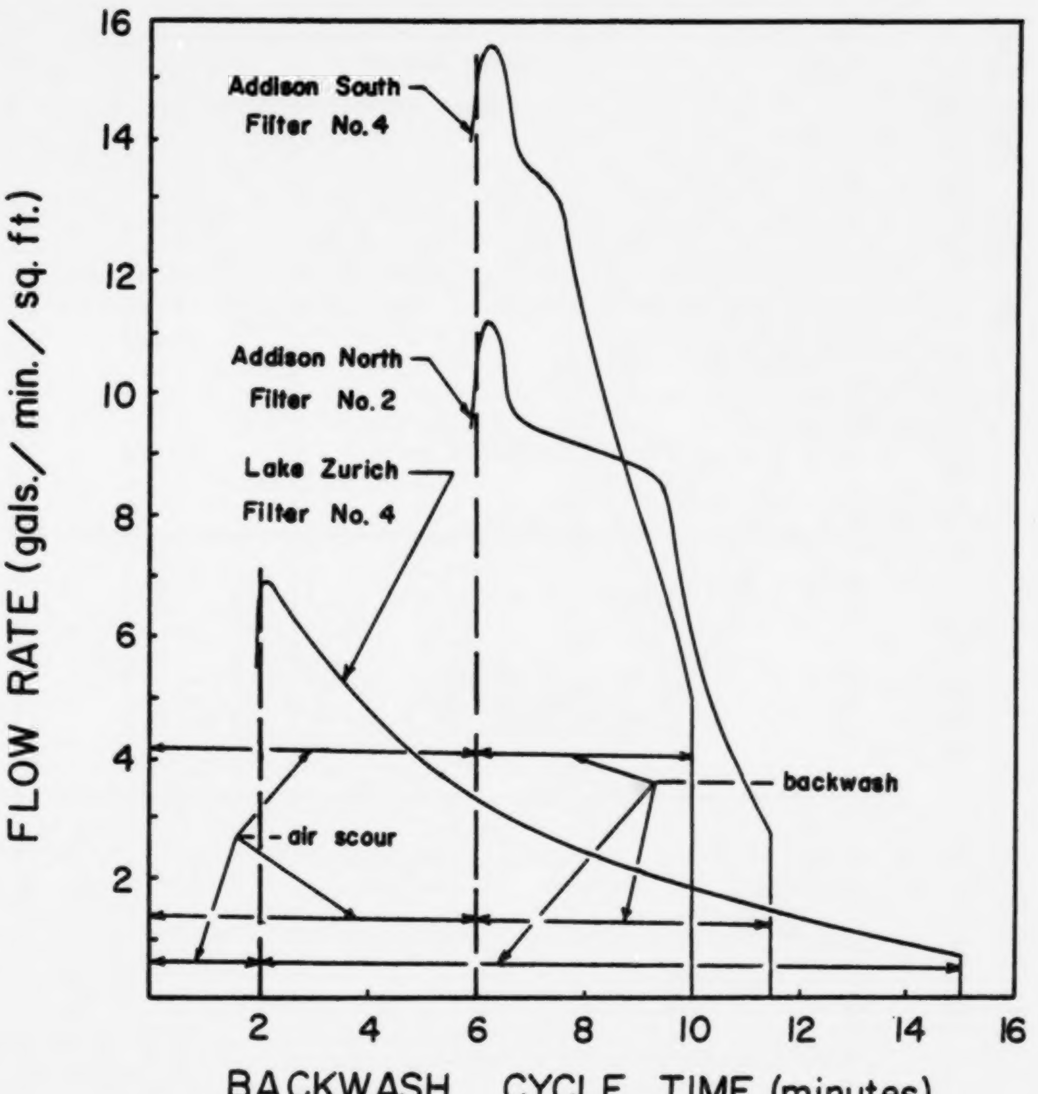


Figure 5. Flow rate vs. backwash cycle time.

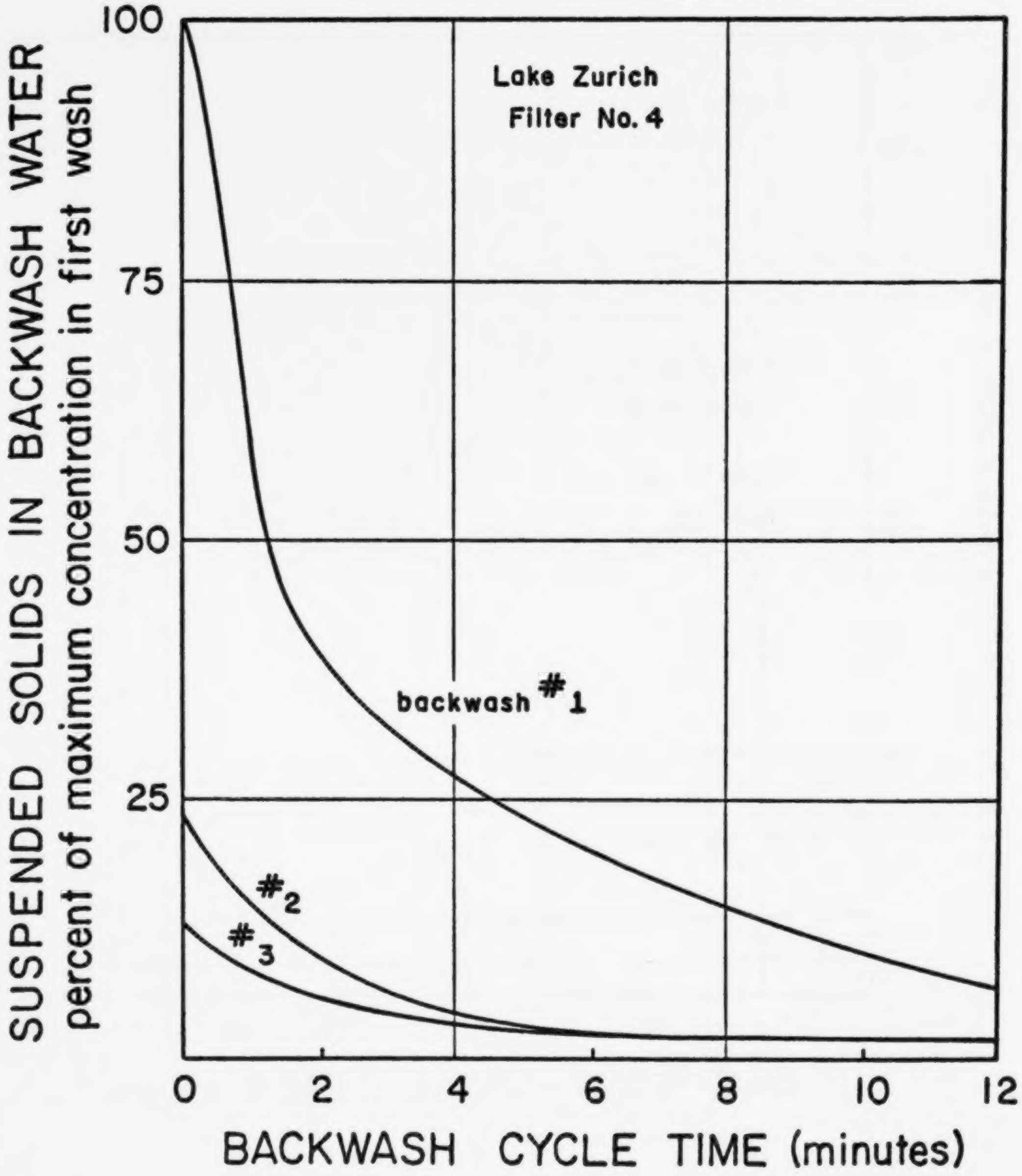


Figure 6. Suspended solids concentration vs. backwash cycle time.

appears to be insufficient to develop complete fluidization. The flow rate varies during the cycle because of the declining head in the backwash storage tank. During the latter part of the cycle, flow rate is insufficient to maintain fluidization for the filters with smaller media at Lake Zurich.

At the Lisle and Marionbrook plants (Eimco design), initial rate varied from 13 to 18 gpm/sf and after 3 to 4 min. the rate dropped to 10 gpm/sf. For these filters, the backwash rate can be adjusted by changing the opening size on the discharge line.

Tests were made at the Addison South (No. 4) and Lake Zurich plants to determine the effectiveness of the backwash cycle in cleaning the media. After an initial backwash, filters were backwashed 2 more times as soon as the storage tank refilled. A plot of backwash suspended solids concentration as a percent of the maximum concentration in the first wash vs time is shown in Figure 6 for 3 consecutive washes for Lake Zurich. The suspended solids concentration decreases rapidly with time during the first cycle. The solids yield per backwash cycle was determined by summing the product of flow times solids concentration per unit of time. For Lake Zurich, the ratio of percentage of solids recovered during the 1st, 2nd, and 3rd washes was 75:15:10, respectively. Thus, about 25% or more washable solids are carried in inventory after one backwash.

Filter media cleaning was much less effective for the large media at Addison South (No. 4) where little fluidization takes place. For this filter, the ratio of percentage solids recovered during the 3 cycles was 50:25:25, respectively. Thus, 50% of the washable solids remained in inventory after one backwash.

These dual media filters are not cleaned as effectively as unstratified coarse single medium sand filters as reported by Dahab and Young (1972), as evidenced by the large solids inventory after one backwash cycle. However, data obtained on filter performance indicate that the high solids inventory does not appear to result in decreased particle collection efficiency. The removal efficiency for the small diameter media filters at Addison South, which are cleaned more effectively, was similar to the large diameter media filters at comparable flow rates during Phase 1. A similar result was obtained in later phases of the study.

Dahab and Young (1977) contended that mudball formation is prevalent when wash conditions are not conducive to breaking up and washing mudballs from the freeboard space. They considered poor freeboard solids washout to be one undesirable characteristic of dual media filters, since the solids may provide nuclei for mudball formation.

From examination of both pilot and full scale dual media filters in this study, it was found that freeboard solids washout is not complete and as much as 1/8 to 1/2 inch of solids settle back onto the media surface after a wash. In pilot column tests run in parallel with the full scale filters at Addison South and Marionbrook, Minix (1979) found these solids formed a porous structure that contributed little to accumulation of residual headloss. Presumably, since each of the filters has air scour or surface wash these solids did not get the chance to contribute to mudball formation. With the above mentioned characteristics and wash volumes of only 30 to 40% of those normally used, mudball formation or filter bed cracking has never been observed in these dual media filters. However, evidence of media packing (mudballing) was found in the Neptune Microfloc installation, particularly in the corners of the rectangular basin where the rotary surface wash was ineffective. This was in spite of the 17 gal/min/ft$^2$ wash rate and wash volumes three to four times the other dual media designs (Table 2). Also as expected all designs that use auxiliary air (or surface wash) experienced rapid deterioration of performance if the auxiliary malfunctioned.

## Media Integrity

Loss of media integrity, i.e. the loss of media, change in gradation or intermixing, occurs to a varying degree in these dual media filters. Anthracite loss, the most dramatic phenomenon, is noted on Table 3 for most dual or multi-media filters. Media loss is somewhat inexplicable based on the relatively low backwash rates (subfluidization in some cases) in all the gravity wash filters. In fact, losses are associated with mechanical or control system failures. Control systems and valve mechanisms often suffer corrosion damage causing malfunctions, such as continuation of air scour during backwash and resulting media loss. In one filter, a structural failure in the bottom of the backwash storage tank caused leakage and loss of media during air scour. Attrition loss in the absence of such incidents is normally only 5 to 10 percent per year for most filters, except for one system where anthracite losses are large due to high backwash rates. The least amount of media loss occurred for the relatively large media at Addison North and South. Since there is little difference in particle collection efficiency for various multimedia configurations, design considerations should generally favor large diameter media.

Cleasby and Baumann (1974) state that for dual media filters the $d_{90}$ anthracite: $d_{10}$ sand ratio is the most important factor in determining the amount of intermixing of anthracite and sand at the dual media interface. The calculated ratios of 4.5 - 5.0 suggest that a relatively mixed interface should result. Pilot columns paralleling full scale operation at two sites developed up to 8 inches intermix zones but did not contribute excessive headloss, Minix (1979). A possible explanation is that most of the intermixing occurred during air scour rather than backwashing (subfluidization) and was correspondingly less dramatic. Core samples from the full scale filters showed that the sand tended to accumulate near the filter walls to some extent, and that the depth of anthracite was largest near the center.

No specific detailed data on media cleaning and integrity were obtained for the shallow bed single media sand filters. Even though able to produce a satisfactory effluent at 60 mg/$\ell$ influent solids, the Environmental Elements filter developed an associated problem. Grease and high solids carryover to the filters from the secondary under these conditions provided mudball nuclei that resulted in several inches of media loss over a period of such incidents. Eventually, the "clean bed" headloss increased enough that complete media replacement was required. With a high or higher grease and solids the Hydro Clear installation never experienced either of these problems because of a detergent and hypochlorite media wash system.

## Mechanical and Electrical Control Systems

It is difficult to make a direct comparison of control systems for the plants because of the variable age of equipment. However, some general observations can be made. No problems occurred during the study for the Hydro Clear and Environmental Elements designs. Frequent problems occurred for the Neptune Microfloc plant; this equipment is scheduled for retirement from service soon.

Frequent maintenance is a necessity for the plants with the backwash storage tank located above the filter media compartment. Corrosion problems are severe after about 5 years due to the high humidity in the filter buildings. The air cylinder operated backwash and air valves were observed to stick frequently in the open position. However, the increased maintenance for these designs is partially offset by the reduction in operating labor required as compared to the Environmental Elements design which required frequent washdown and cleaning of the filter walls.

## CHAPTER VI

# CLARIFICATION EFFICIENCY MODELS OF GRANULAR BED FILTERS

## INTRODUCTION

Filtration of secondary effluents through granular media is considered to be one of the most cost effective processes in upgrading effluent quality to meet more stringent discharge standards. Suspended solids, consisting of flocculated microorganisms or cell debris and inorganic particulates, are separated from the liquid phase by collection at the surface and within the pores of an unconsolidated porous medium.

Most recent studies of tertiary wastewater filtration have been directed toward filter media selection and least cost design and optimization; little attention has been given to the effect of suspension characteristics on filter clarification efficiency. No method has previously been developed to determine filter clarification efficiency a priori without pilot-scale testing.

The purpose of this chapter is to review pertinent filtration and clarification literature and provide the basis for development of operational mathematical models to describe wastewater filter clarification efficiency. These models are intended to provide a uniform basis for examination of data on full-scale filter clarification efficiency.

## CURRENT WASTEWATER FILTER DESIGN

Wastewater filter design involves specification of filter type, process arrangement, flow rate, and media type, size and depth. Chemical addition to promote aggregation/destabilization of the colloidal fraction ahead of filters is generally not practiced, particularly for small plants.

Where economics dictate or permit, design criteria are developed from pilot-scale tests. In many cases design is based on empiricism and rules of thumb derived from potable water filtration and ten or more years of experience in tertiary wastewater filtration in the United States (Cleasby and Baumann, 1974) and Great Britain (Oakley and Cripps, 1969; Guiver and Huntingdon, 1971; Tebbut, 1971; Michaelson, 1971). Filter suspended solids removal efficiency is specified with tongue in cheek since reliable, simple correlations of filter efficiency have yet to be developed for wastewater suspensions.

## PARTICLE COLLECTION MODES

Particle collection in granular media filtration involves complex interactions between a number of physical and chemical forces. These are manifested in terms of a number of variables: media type, size, and depth, filtration rate, influent suspended solids concentration, influent particle size distribution, type of secondary process, and flocculation characteristics of solids. The latter three will also be a function of the type of secondary process.

Much of the work on filtration theory prior to 1960 can be classified as physical, and was concerned primarily with media size and depth, deposit distribution within the filter, and headloss development.

Beginning approximately 15 years ago, emphasis was placed on both the physical and chemical aspects. Beginning around 1964 (Gregory, 1964), particle collection was considered to be a two-step process consisting of transport to the vicinity of the collector (grain) and attachment to the grain or already deposited solids. The former was considered physical and the latter chemical. Classical particle transport mechanisms were identified as gravity settling, interception, and Brownian diffusion; and attachment forces as van der Waal attraction, electrical double layer, and specific chemical interactions (Ives, 1969; O'Melia and Stumm, 1967).

## Depth Filtration Models

The bases for most physical, depth filtration models describing evolution of clarification efficiency with depth and time are the first order deposit and mass continuity equations proposed by Iwasaki (1937).

$$-\frac{\partial C}{\partial L} = \lambda C \ , \quad \text{and} \tag{3}$$

$$-\frac{\partial C}{\partial L} = \frac{1}{Q}\frac{d\sigma_s}{dt} \ , \tag{4}$$

where $C$ = concentration of suspended material,

$L$ = filter depth,

$\lambda$ = filter coefficient,

$t$ = time,

$\sigma_s$= specific deposit--volume solids/volume filter, and

$Q$ = superficial filtration velocity.

For initial conditions, integration and rearrangement of Equation 3 gives

$$-\frac{1}{L}\,\mathrm{Log}_e \frac{C}{C_o} = \lambda_o \tag{5}$$

where $C_o$ = initial concentration of suspended material.

As filtration and deposition of suspended material progresses, the value of the filter coefficient $\lambda$ changes. A variety of theoretical and empirical models have been proposed to relate $\lambda$ to specific deposit (Herzig, Le Clerc, and Le Goff, 1970). This research has been summarized elsewhere and will not be reviewed here (Ives, 1971).

FitzPatrick (1972) and FitzPatrick and Spielman (1973) presented a model of initial filtration ($\lambda_o$) derived from extending and solving the trajectory equations of Spielman and Goren (1970) for flow past a spherical medium particle. By this theory, which contains no adjustable constants, they were able to reproduce to a factor of 2 the collection efficiency ($\lambda_o$) over a range of four orders of magnitude.

Recently, Ghosh, et al. (1975), have applied the Spielman and FitzPatrick (1973) model for particle capture to analyze wastewater filter performance. They obtained good correlation of collection efficiency over the 2 to 10 μm particle size range. However, particle sizes in secondary effluent suspensions are not usually confined to this limited range.

Minix (1979) conducted on-site pilot scale studies in parallel with the full-scale sampling program at the Addison South and Marionbrook plants during Phase 1. He found clarification efficiency a weak function of run time and filter depth. Comparisons of his data with the Spielman and FitzPatrick (1973) model showed significant underprediction for anthracite layers but slight overprediction for sand layers.

Based on pilot-scale experimental results for a relatively limited range of secondary effluent properties, Tchobanoglous and Eliasson (1970) developed a depth filtration semiempirical clarification model, viz.

$$\frac{dC}{dX} = - \left[ \frac{1}{(1 + a\ X)^n} \right] \lambda_o C \quad \text{, and} \tag{6}$$

C = concentration--mg/$\ell$,

X = distance in inches,

$\lambda_o$ = initial removal rate per inch, and

a and n = experimentally determined constants.

If n is equal to zero, a logarithmic removal of particles with depth occurs as in Equation 5. If n is greater than zero, a larger removal occurs in the upper layers. In their work, the value of n was found to be 2 and they concluded that straining was a significant particle collection mode.

Fuerstein (1976), using concepts developed by Kavanaugh (1974), generated functional forms for describing depth filtration breakthrough and limiting headloss in wastewater filtration. These models require that several parameters (effective specific deposit, maximum depth averaged collector efficiency, and specific deposit-hydraulic gradient proportionality constant) be determined experimentally from pilot-scale tests.

## Forms of Filter Coefficient

Wright, et al. (1970), summarized the results of granular bed filtration studies by numerous investigators who related the initial filter coefficient ($\lambda_o$) as a power function of several variables with constant coefficients ($\lambda_o = a\ Q^b\ d_p^c\ d_m^d$). Table 7 summarizes only the functional relationships they reported for variables measured in this study. Both discrete and flocculent suspensions but no secondary effluents were used in the reported studies. The coefficients varied for Q from -0.3 to 4, for $d_p$ from -1 to 0.3, and for $d_m$ from -1 to -3.

FitzPatrick (1972) derived functional forms for the dependence of $\lambda$ on system variables. These are shown in Table 8, along with dependencies derived from his filtration experiments using suspensions and media with well-defined properties. He found that the coefficient varied for Q from 0 to -1, for $d_p$ from -.67 to 2, and for $d_m$ from -1 to -3.

Straining

A large portion of the mass of the suspended solids in secondary effluents is of sufficiently large particle size so that straining will occur. This has been suggested as a significant particle collection mode (Craft and Eicholz, 1970; Tchobanoglous and Eliasson, 1970). Straining can occur at and near the surface of the filter medium and deeper in the filter in the crevices between adjacent medium particles (Payatakes and Brown, 1977). In design of potable water filters, straining is avoided in order to utilize the full depth of the filter medium and maximize run length. Straining does not have as large a tendency to occur for potable water filtration as compared to direct wastewater filtration because of lower solids loading and absence of coarse particulates. A good understanding of the straining filtration process is still not available at this time (Payatakes and Brown, 1977).

Hall (1957), using solely geometric arguments, developed a relation for the filter coefficient indicating a -1.5 power dependence on media diameter if straining was dominant. Craft and Eicholz (1970) indicated the filter coefficient should be proportional to $(d_p/d_m)^{3/2}$ if straining dominates. Heertjes (1973) and Tiller (1975) have developed models relating to formation of cakes and precoats at the surface of filter septums, which may be closely analogous to straining at the surface of granular media.

Kavanaugh (1974) explored possible relationships between $\bar{d}_p/d_m$ and the number flux ($J_{N_O}$) of particles to the filter beds that would experience straining. His own data included both unflocculated and flocculated suspensions of latex microspheres and $TiO_2$ colloids, and data from the literature included only unflocculated suspensions and unisize filter media. From a plot of the data, he developed a semiempirical correlation for unflocculated suspension particle size $d_p$ that would experience straining when challenging a unisize granular bed of diameter $d_m$ at concentration $N_o$ and flowrate Q (or applied particle flux of $Q N_o = J_{N_O}$):

$$\bar{d}_p \le 0.25\ d_m\ J_{N_O}^{\ -0.2} \tag{7}$$

His correlation showed that, as should be expected, interstitial straining depends not only on geometric variables ($d_m$) but also on flowrate which is

Table 7. Power function relationships for filter coefficient ($\lambda_o$) - After Wright, et al. (1970) ($\lambda_o = -\text{Log}\,\frac{C}{C_o} = aQ^b d_p^{\,c} d_m^{\,d}$)

| | Power Function Coefficient | | |
|---|---|---|---|
| Investigator | Q | $d_p$ | $d_m$ |
| Iwasaki (1937) | -0.3 | - | -1 |
| Stein (1940) | - | - | -3 |
| Fair (1951) | - | - | -1.7 |
| Ling (1955) | - | - | -1.5 |
| Stanley (1955) | -1.6 | - | -2.5 |
| Hall (1957) | | | |
| Straining | - | - | -1.5 |
| Settling | - | -1 | -1 |
| Mintz and Kristhul (1960) | -0.7 | - | -1.7 |
| Mackrle and Mackrle (1961) | -1 | - | -2 |
| Maroudas and Eisenklam (1965) | -1 | - | - |
| Ives and Sholji (1965) | -1 | - | -1 |
| Ives and Ison (1967) | -4 | 0.3 | -1.4 |

Source: Wright, A., Kavanaugh, M. and Pearson, E., "Filtration Kinetics in Water and Wastewater," First Annual Progress Report - SERL College of Engineering, University of California, Berkeley, 1970. (References keyed to bibliography in report.

Table 8. Power function relationships for filter coefficient ($\lambda_o$) - After FitzPatrick (1972) ($\lambda_o = -\mathrm{Log}\,\frac{C}{C_o} = aQ^b d_p{}^c d_m{}^d$)

| Investigator | Power Function Coefficient | | |
|---|---|---|---|
| | $Q$ | $d_p$ | $d_m$ |
| Experiment | | | |
| $N_{Grs}$* < 1.0 | -.1 to -.5 | 1-5 | -2.3 to -1.7 |
| $N_{Grs} > 10$ | -1 | 1.8-2.2 | - |
| Classical Theories | | | |
| Interception | 0 | 2 | -3 |
| Gravity | -1 | 2 | -1 |
| Diffusion | -.67 | -.67 | -1.67 |
| Straining-Hall(1957) | 0 | 1.5 | -1.5 |

---

*Dimensionless gravity settling group, the larger the value of $N_{Grs}$, the greater the effect of particle sedimentation in the capture process.

proportional to $J_{N_O}$.

Shea and Malis (1971) developed a computer model of the microscreening process for treatment of primary and secondary effluents from laboratory and field studies. For the rotary drum units tested, straining across the screen openings and intercepted mat of solids is clearly the dominant particle removal mode. They found that the particle size distribution of the process influent was the key parameter in determination of particle removal efficiency. Flocculation properties of influent suspensions were not measured.

At present, no definitive theory has been developed and tested for straining in granular media filtration of secondary effluents. In addition, no theory exists to determine a priori whether straining or in-depth filtration will be the dominant particle collection mode. However, as explained in subsequent sections, hypotheses are advanced that relate suspension properties to semi-empirical clarification models.

## SUSPENSION PROPERTIES

Little information is available in the literature on the role of suspension properties in the tertiary wastewater filtration process. Secondary effluent suspensions may have a wide range of solids concentrations as well as particle size and surface chemistry. Particle size distributions are difficult to obtain experimentally, particularly for the larger particles because the number concentrations are so low and particle size may be altered in the sampling or counting method used (Treweek and Morgan, 1977a).

Hsiung (1972) was the first to utilize refiltration techniques on secondary effluent suspensions to characterize performance of tertiary wastewater filters. The refiltration technique was first developed by Lamer and Smellie (1956), utilizing the Kozeny-Carman equation. This technique involves filtration of three or more samples of different volumes through microporous filter paper and measurement of the time for refiltration of the filtrates.

Hsiung utilized the Carman equation for flow through a filter cake of constant and known thickness:

$$\frac{V}{t} = \frac{\Delta P g A \epsilon^3}{K \mu L_t S^2} \qquad (8)$$

where $V$ = volume of sample filtered,

$t$ = refiltration time,

$\Delta P$ = pressure drop across cake,

$g$ = acceleration of gravity,

$\epsilon$ = porosity of cake = $1 - (W/AL\rho)$,

$A$ = filter cross sectional area,

$W$ = weight of solids in cake,

$L_t$ = thickness of cake

$\rho$ = bulk density of cake,

$\mu$ = viscosity of fluid passing through cake,

K = constant, and

S = surface area of particles in unit volume of cake.

If $\Delta P$, g, A, K, and $\mu$ are constant, Equation 8 reduces to

$$\frac{V}{t} = K' \left(1 - \frac{1}{AL_t\rho}\right)^3 \frac{1}{L_t S^2} \tag{9}$$

Assuming all solids are removed by filtration, then

$$W = V\,C_0 \tag{10}$$

where $C_0$ is secondary effluent suspended solids. From Equations 9 and 10:

$$VC_0 = AL_t\rho - \frac{AL_t\rho\; L_t^{1/3}\; S^{2/3}}{K''} \left(\frac{V}{t}\right)^{1/3} = R - \frac{R}{G}\left(\frac{V}{t}\right)^{1/3} \tag{11}$$

The terms $R = AL_t\rho$ and $G = \left(\frac{K'''}{L_t S^2}\right)^{1/3}$ are the intercepts on the ordinate and abscissa axes, respectively, when $VC_0$ is plotted against $(V/t)^{1/3}$. Hsiung proposed an empirical factor, $E = (R^{1/3}G)^{1/2}$, and obtained data for pilot filtration of secondary effluents from four plants at a constant rate of 5 gpm/sf. An excellent correlation of E with percentage removal of suspended solids was obtained.

Hsiung (1975) did not discuss the origin of the apparently empirical factor $E = (R^{1/3}G)^{1/2}$ used to correlate filter suspended solids removal efficiency in his studies. However, if unisized particles of diameter $d_p$ and of number concentration n make up the suspension, then in a unit volume of filter cake, the number concentration is:

$$n = \frac{1 - \varepsilon}{\frac{\pi}{6} d_p^3} \tag{12}$$

where $\varepsilon$ is the bulk porosity of the cake and the surface area per unit volume of cake is

$$S = n \times \pi d_p^2 \tag{13}$$

or

$$S \alpha\, d_p^{-1} \tag{14}$$

Assuming cake cross sectional area A and bulk solids density $\rho$ defined in Equation 9 are constant implies that L is proportional to R. Thus,

$$G = \left(\frac{k'}{L_t S^2}\right)^{1/3} = \left(\frac{k'' d_p^2}{R}\right)^{1/3} = \left(\frac{k'''}{RS^2}\right)^{1/3} , \tag{15}$$

or

$$d_p = k'''' R^{1/2} G^{3/2} \tag{16}$$

or

$$d_p \propto E^3 \tag{17}$$

Then E is really a semiempirical factor proportional to the cube root of the particle diameter. It follows then that it may be possible to characterize the extent of straining by the refiltration parameter E or the measured mean particle size. If this hypothesis is correct, inclusion of E in power function relationships for forms of the filter coefficient should result in a significant improvement in correlations if straining is the dominant particle collection mode.

Treweek and Morgan (1977b) measured the extent of flocculation of an *E. coli* suspension produced by the addition of cationic polymers. Methods used to characterize the extent of flocculation were turbidity, electrophoretic mobility, light scattering, Coulter counting, and refiltration methods. Of the techniques used, they found that the refiltration method was the best technique for determining the effectiveness of the polymers in flocculating *E. coli*. Their results confirm that refiltration parameters characterize the extent of flocculation but do not imply that they will also characterize filter performance.

## MODEL DEVELOPMENT

It would be expected that particle attachment would depend on both particle and media surface properties. As shown in Chapter V, the full-scale dual media filters evaluated in this study carry a large solids inventory after backwashing. Pilot-scale filters can be backwashed much more effectively although any wastewater filter cannot be completely cleaned since a microbial film always stays on the media. It follows that particle-particle surface chemical interactions may well be more important than particle-media interaction in defining particle capture and clarification efficiency.

A large number of suspension properties could be included in a correlation of filter clarification efficiency. Possibilities include solution chemistry, total suspended solids, particle size, zeta potential, density, shape, floc strength, and biological identification.

Inclusion of too many parameters makes correlation unwieldy and may require an excessive number of measurements and a large data base. Several of the above parameters which may be important are difficult or impossible to quantify at present (e.g., biology, floc strength). Most will be distributed and may not show a single central tendency. This suggests that in the short run a more practical approach may be to use lumped or mean parameters to characterize suspension properties. Examples include refiltration parameters, mean particle size and variance, mean electrophoretic mobility, and surface charge. The latter two properties are measured according to methods presented by Novak, et al. (1977).

If in-depth filtration is the mode of capture, theory suggests correlating the filter coefficient $\lambda$ as:

$$\lambda \alpha - \frac{1}{L} \text{Log} \frac{C}{C_o} = f(Q, d_m, d_p \text{ or } E) \ , \qquad (18)$$

where f is a power function with constant coefficients.

If filters are overdesigned with respect to depth and the bulk of the solids capture occurs in the upper layers, even though in-depth filtration may still be the mode of capture, it may be hypothesized that:

$$\text{Log} \frac{C}{C_o} = f(C_o, Q, d_m, d_p \text{ or } E). \qquad (19)$$

In this study, the largest measured variation of $C/C_o$ is a factor of 10 (0.06 to 0.6 for Phases 2, 3 and 4), thus it is just as reasonable to hypothesize that:

$$C = f(C_o, Q, d_m, d_p \text{ or } E). \qquad (20)$$

If straining filtration dominates, it is not clear what dependence the filter coefficient should follow since a theoretical interpretation is not available at present. Nevertheless, straining or surface capture should be confined to a smaller depth of the media as compared to in-depth particle capture. In that case, it would then be expected that Equation 18 would provide a poorer correlation of the data than Equations 19 and 20, and that the exponent for E in Equations 19 and 20 would be higher for straining as compared to in-depth particle collection.

These hypotheses are tested in Chapters VIII and X, using multiple regression techniques with log transformations. In Chapter VIII, models with C, $C_o$, Q, L, and $d_m$ are tested. Additional approaches for segmenting data based on dominant in-depth or straining particle collection modes are discussed in the following section.

## CHARACTERIZATION OF STRAINING AND IN-DEPTH FILTRATION FOR FULL-SCALE FILTERS

From theory, headloss buildup vs. time should be linear or polynomial for in-depth filtration (Ives, 1971) and logarithmic for straining or sieving (Tiller, 1975; Cleasby and Baumann, 1974). Where total headloss data during runs or backwash frequency data were obtained in this study, filter performance can be analyzed by postulating that straining is the dominant particle collection mode for high headloss buildup and in-depth filtration for low headloss buildup. In addition, straining is expected to be the dominant suspended solids collection mode for the single medium sand filters at the Des Plaines River and Romeoville plants.

Because of the inherent limitations of full-scale plant studies, the resources required to monitor headloss buildup and particle collection at intermediate depths in the filter media would have been prohibitive, within a reasonable study budget. This precluded a more exhaustive study to characterize particle collection mode. However, a significant effort to characterize collection mode was undertaken in Phase 1 and reported elsewhere (Minix, 1979).

As shown in Equation 17, E is proportional to the cube root of particle size. Since the role of straining increases with larger particle size and E, both can be used to aid in separation of data for analysis. In Appendix D, a dimensional straining group ($N_{STR}$) is developed to use as an aid in segmenting data (Chapter X).

# CHAPTER VII

# FREQUENCY DISTRIBUTIONS OF SECONDARY AND FILTER EFFLUENT PARAMETERS

## INTRODUCTION

This chapter describes the results of statistical studies of secondary effluent and granular media filter effluent parameters. Parameters included were flow rate, BOD, and suspended solids. All data are based on flow proportioned composite samples. The normal, log normal, rectangular, Poisson, and negative binomial distributions were examined to determine their utility for describing parameters for the Phase 1 data in 1976 for the Addison North and South (Filter No. 2) plants. Kolomogorov-Smirnov (K-S) tests were used to examine all Phase 1 data and the extent of autocorrelation was determined. Insufficient data were obtained for these statistical analyses in Phases 2, 3 and 4.

Knowledge of frequency distributions is essential for the proper design of data collection programs for survey and enforcement monitoring, and for establishment of effluent limitations. There are several reports in the literature in which the frequency distributions for effluent parameters have been characterized to some extent (Hoogerhyde, 1973; Eckenfelder and Roth, 1974; Dean and Forsythe, 1975; Crandall, 1975). Hoogerhyde (1973) indicated that tertiary filter effluent suspended solids are normally distributed. Dean and Forsythe (1975) have argued that effluent parameters from a wide variety of treatment processes should have a log normal distribution. There are also other frequency distributions which might adequately characterize effluent parameters.

## STATISTICAL ANALYSES

In the context of this chapter, a frequency distribution is a tabulation or a graphical representation of the relative frequency of occurrence of an event corresponding to a continuous random variable. It may be represented as a probability density function or as a cumulative distribution function. Several common theoretical frequency distributions were examined to determine their utility in describing effluent quality parameters. These distributions are the normal (Gaussian), the log normal, the rectangular (uniform), the Poisson and the Negative binomial. The probability density functions for these distributions are given in Table 9. In this table $m_x$ is the arithmetic mean, $\sigma_x$ is the standard deviation, $\breve{m}_x$ is the geometric mean and $\sigma_{\ln x}$ is the geometric standard deviation. The Poisson parameter, $\nu$, is equal to the mean and variance. The k parameter for the negative binomial distribution is related to the mean and variance, as shown in the table, and is a measure

Table 9. Standard probability models

| Model | Probability Density Function[**] | Parameter (s) |
|---|---|---|
| Poisson: | $p(x) = \frac{\nu^{x} e^{-\nu}}{x\,!}$ | $\nu$ |
| Normal: | $p(x) = \frac{1}{\sigma_x \sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{x - m_x}{\sigma_x}\right)^2\right]$ | $m_x$ , $\sigma_x$ |
| Log Normal[∓]: | $p(x) = \frac{1}{x\sqrt{2\pi}\,\sigma_{\ln x}} \exp\left\{-\frac{1}{2}\left[\frac{1}{\sigma_{\ln x}} \ln\left(\frac{x}{\breve{m}_x}\right)\right]^2\right\}$ | $\breve{m}_x$ , $\sigma_{\ln x}$ |
| Negative[*] Binomial: | $p(x) = \frac{\Gamma(k + x)}{\Gamma(x + 1)\,\Gamma(k)} \left(\frac{m_x}{m_x + k}\right)^x \cdot \left(1 + \frac{m_x}{k}\right)^{-k}$ | $\sigma_x^2 = m_x + \frac{m_x^2}{k}$ |
| Rectangular[++]: | $p(x) = \begin{cases} \frac{1}{b+a}\ , & a \le x \le b \\ \text{elsewhere} & 0 \end{cases}$ | $m_x = a + \frac{b-a}{2}$<br>$\sigma_x^2 = \frac{(b-a)^2}{12}$ |

[**] x - a continuous random variable

[*] k - denoted as a measure of extreme variance (Thomas et. al., 1956)

[±] $\breve{m}_x$ and $\sigma_{\ln x}$ - respectively the mean and standard deviation of the natural logarithms of the raw data.

[++] x - defined for arbitrary range a to b.

of extreme variance.

It will be shown later that data are sufficiently independent so the application of theoretical frequency distributions is valid. A major objective of this portion of the study was to determine if effluent quality data fit one of these common one or two parameter frequency distributions. It is quite likely that better fits could be obtained if three or four parameter distributions were tried. However, using additional parameters requires additional data and, in general, complicates any statistical tests to be made. The multiparametric distributions are normally not used unless there is some specific advantage to be gained.

The selection of the frequency distribution giving the best fit is discussed later. The selection was made using the Chi-square ($\chi^2$) test, the Kolomogorov-Smirnov (K-S) test, and a visual comparison. The parameters for each distribution were calculated from the data. Then, using the probability density functions and the calculated parameters, expected frequencies for observations were calculated. The $\chi^2$ test indicates that the data actually fit the theoretical distribution at a given level of significance if the sum of the differences between the observed and expected frequencies squared divided by the expected frequencies is less than or equal to a given value of a $\chi^2$ distributed variable with degrees of freedom equal to the number of class intervals minus one more than the parameters estimated for the theoretical distribution.

The K-S test is also a quantitative goodness of fit test and is based upon the deviation between the hypothesized cumulative distribution function and the observed cumulative histogram. The cumulative distribution functions for the observed data and the theoretical distribution are computed as well as the difference between them at each level. The largest difference (positive or negative) is determined and, from that, the Kolmogorov-Smirnov Z. The larger the value of Z, the less likely it is that the observed and theoretical distributions are the same. A visual fit of the data is obtained by comparison to a line generated from the parameters on normal and log normal cumulative probability paper (probit scale). Data are compared to a line with the same $x_{50}$ (median) and $\sigma$ or $\sigma_{\ln x}$ as the case may be. Agreement may be good near the central tendency of the data for either distribution but such plots permit a judgment of which model fits the data best in the "tails" of the distribution.

Autocorrelation is a measure of the relative dependence of the value of a parameter to its value at an earlier time in a time series. To test for the extent of autocorrelation, a plot of the value of the variable after a time interval vs. the value at the beginning of the interval is prepared. The autocorrelation coeffient ($r_a$) is the bivariate correlation coefficient for the plot. Thus an $r_a$ of plus or minus one indicates a linear increase or decrease with time, respectively, and a value of zero indicates a total independence on the previous value.

## ANALYSIS OF ADDISON NORTH AND SOUTH DATA

### Cumulative Frequency Plots

The variables tested as well as sample means, medians and standard deviations are shown in Table 10. Figures 7A and 7B show the distributions of daily average filter flow rates (gpm/sf) for the Addison North Plant on a log probability plot and a normal probability plot, respectively. The straight line on each plot indicates where the data would be if the fit were perfect. Both probability plots (Figures 7A and 7B) show a reasonable fit at intermediate values of flow. Discrepancies exist between the data and the theoretical distribution at both high and low flows on Figure 7B. Superficial filtration rates greater than 4 gpm/ft$^2$ are associated with precipitation events and could well indicate a separate distribution. The data are truncated at 5 gpm/ft$^2$ because higher flows are diverted to storage facilities for subsequent pumpback to the plant. The actual raw sewage flow would cause this value to be exceeded. The log normal probability plot indicates a better fit throughout the entire range of the data but the break between flows less than 4 gpm/ft$^2$ and greater than this value is still apparent.

In Figures 8A and 8B, the filter effluent suspended solids (C) data from the North Plant are plotted as squares and the secondary effluent suspended solids ($C_o$) are plotted as triangles. From the log probability plot ( 8A ), it appears that both the C and $C_o$ data give a similar level of fit. Both C and $C_o$ appear to show deviation in the tails on the normal probability plot ( 8B ). $C_o$ values above perhaps 70 mg/$\ell$ correspond to "upset" conditions in the contact stabilization process and thus may be representative of a different distribution. From the normal probability plot it is clear that the $C_o$ shows much greater variability (slope of the line) than the C, but this is not apparent from the log probability plot, i.e., the geometric but not the arithmetic standard deviations of the two data sets are similar. Figures 9A and 9B present the plots of total secondary effluent BOD ($C_{ob}$) and total filter effluent BOD ($C_b$) on log probability paper and normal probability paper, respectively. The soluble $C_{ob}$ and soluble $C_b$ data are presented similarly in Figures 10A and 10B. The data for total $C_b$ and total $C_{ob}$ show better fits to the log normal distribution than to the normal distribution. The soluble $C_b$ data fit neither the normal nor log normal distribution very well, while the soluble $C_{ob}$ data show a better fit to the normal distribution.

The data for the Addison South Plant presented on probability plots in Figures 11 to 14 in the same sequence that the data for the Addison North Plant are presented in Figures 7 to 10. For the South Plant, flow and $C_o$ both give reasonable fits to the log normal distribution. C shows a decided curvature on the log probability plot and a much better fit on the normal probability plot. Total $C_b$ data are closer to a normal distribution while soluble $C_b$ appears to be better described by the log normal distribution. Total $C_{ob}$ and soluble $C_b$ both appear to give better fits to the normal distribution.

## Goodness of Fit Tests

The results of the $\chi^2$ and K-S goodness of fit tests are given in Table 11. In addition, a judgment of fit by eye to the probability plots is also included for the normal and log-normal distribution. Goodness of fit results are not shown for rectangular, negative binomial or Poisson distribution on Table 11 because of generally low significance. In a few instances ($C_o$ and

Table 10. Summary of simple statistics for Addison North and South plants.

| Plant | Parameter* | Units | Mean | Standard Deviation | Median | Geometric Standard Deviation | Coefficient of Variation |
|---|---|---|---|---|---|---|---|
| South | Flow | (gal/min/ft$^2$) | 2.06 | 0.46 | 1.95 | 0.21 | 0.22 |
| | $C_{Ob}$ | (mg/l) | 41.8 | 17.1 | 39.5 | 0.45 | 0.40 |
| | Sol.$C_{ob}$ | (mg/l) | 8.6 | 3.6 | 8.0 | 0.45 | 0.42 |
| | $C_b$ | (mg/l) | 9.7 | 4.9 | 10.0 | 0.58 | 0.50 |
| | Sol.$C_b$ | (mg/l) | 6.0 | 3.1 | 4.9 | 0.49 | 0.53 |
| | $C_o$ | (mg/l) | 37.5 | 16.9 | 32.0 | 0.40 | 0.45 |
| | C | (mg/l) | 9.1 | 3.9 | 8.2 | 0.52 | 0.43 |
| North | Flow | (gal/min/ft$^2$) | 3.76 | 0.62 | 3.60 | 0.17 | 0.16 |
| | $C_{ob}$ | (mg/l) | 33.90 | 12.7 | 31.0 | 0.39 | 0.37 |
| | Sol.$C_{ob}$ | (mg/l) | 7.5 | 2.7 | 7.0 | 0.47 | 0.37 |
| | $C_b$ | (mg/l) | 5.1 | 3.9 | 3.5 | 0.78 | 0.77 |
| | Sol.$C_b$ | (mg/l) | 3.8 | 2.9 | 2.2 | 0.79 | 0.77 |
| | $C_o$ | (mg/l) | 43.9 | 18.9 | 39.0 | 0.44 | 0.43 |
| | C | (mg/l) | 6.6 | 3.7 | 5.3 | 0.61 | 0.56 |

$C_{ob}$* - Secondary Effluent Biochemical Oxygen Demand (5 day).

$C_b$ - Filter Effluent Biochemical Oxygen Demand (5 day).

C - Filter Effluent Suspended Solids.

$C_o$ - Secondary Effluent Suspended Solids.

Sol. - Soluble, passing glass filber Reeve Angel R filter

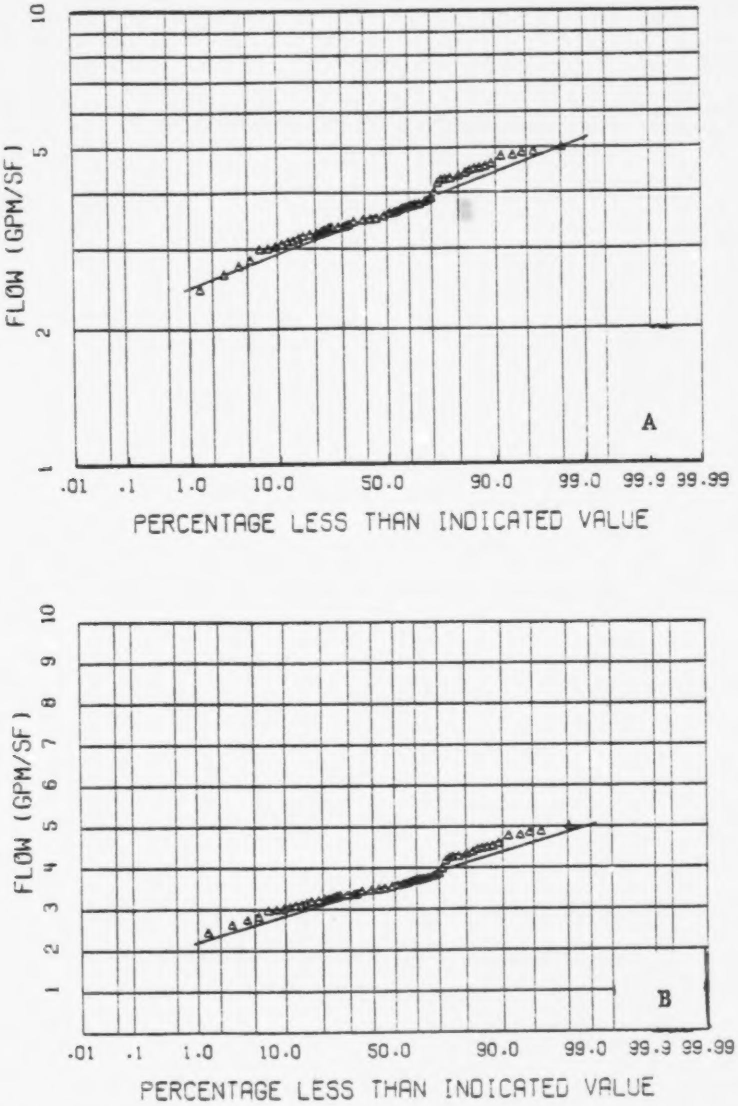
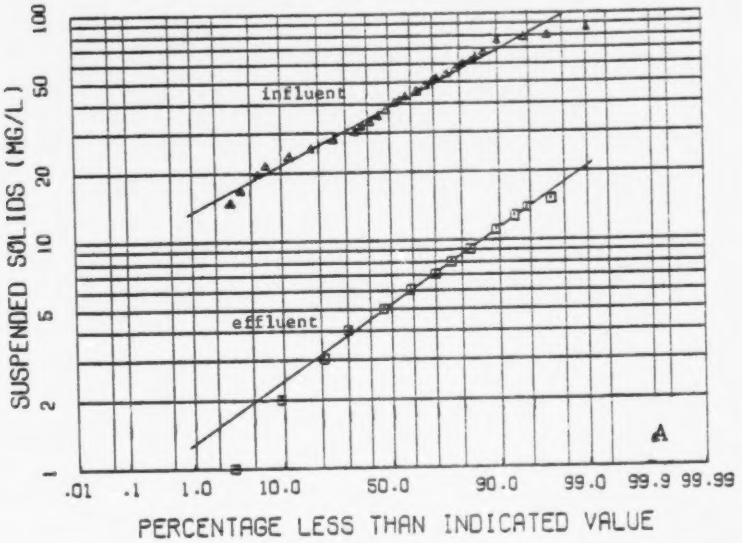


**Figure 7.** Cumulative frequency distribution of filter flow rate, Addison North plant.



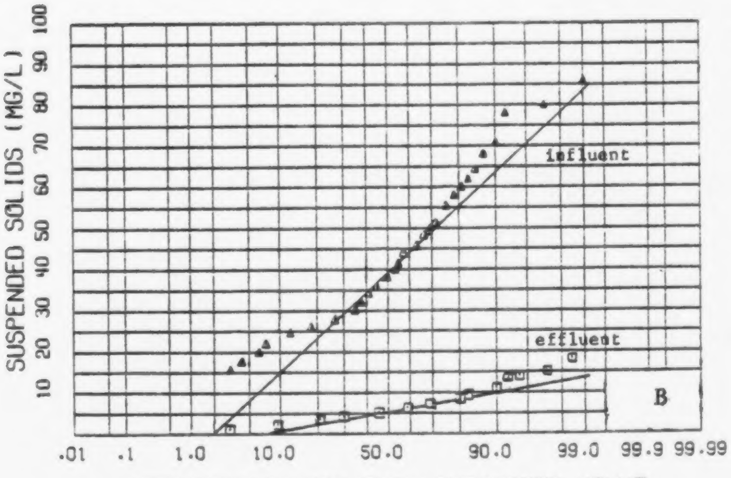


**Figure 8.** **Cumulative frequency distribution of total suspended solids, Addison North plant.**

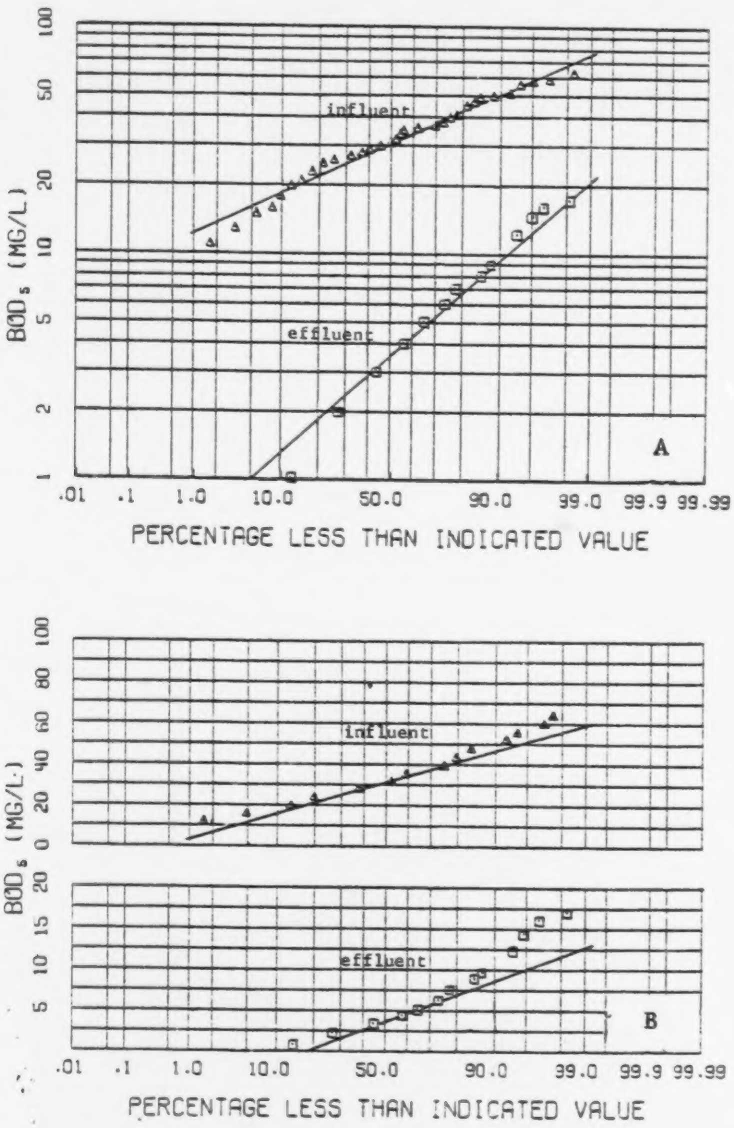


**Figure 9.** Cumulative frequency distribution of total BOD, Addison North plant.

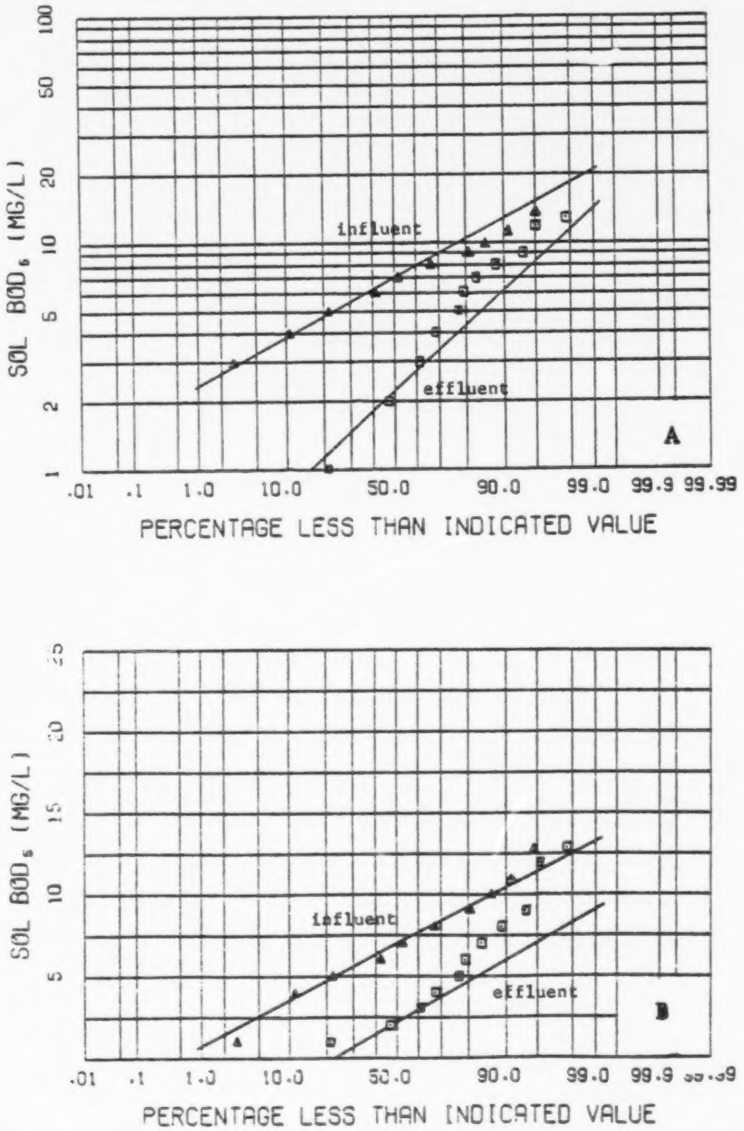


Figure 10. Cumulative frequency distribution of soluble BOD, Addison North plant.

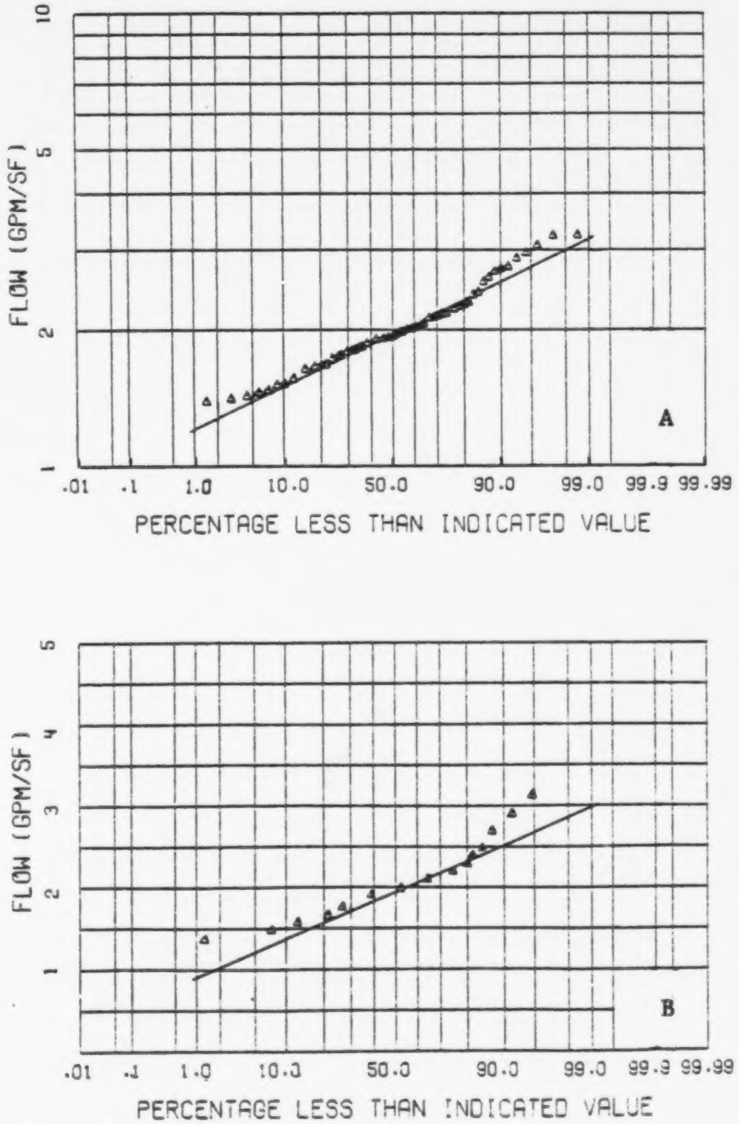


**Figure 11.** Cumulative frequency distribution of filter flow rate, Addison South plant.

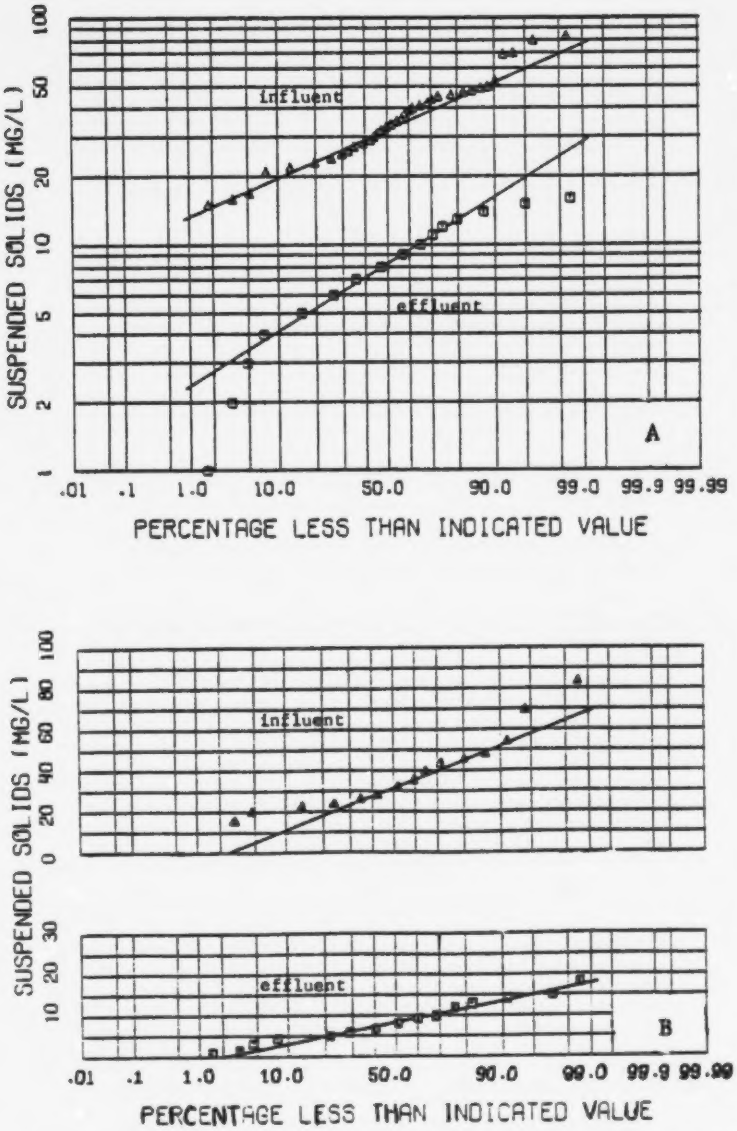


Figure 12. Cumulative frequency distribution of total suspended solids, Addison South plant.

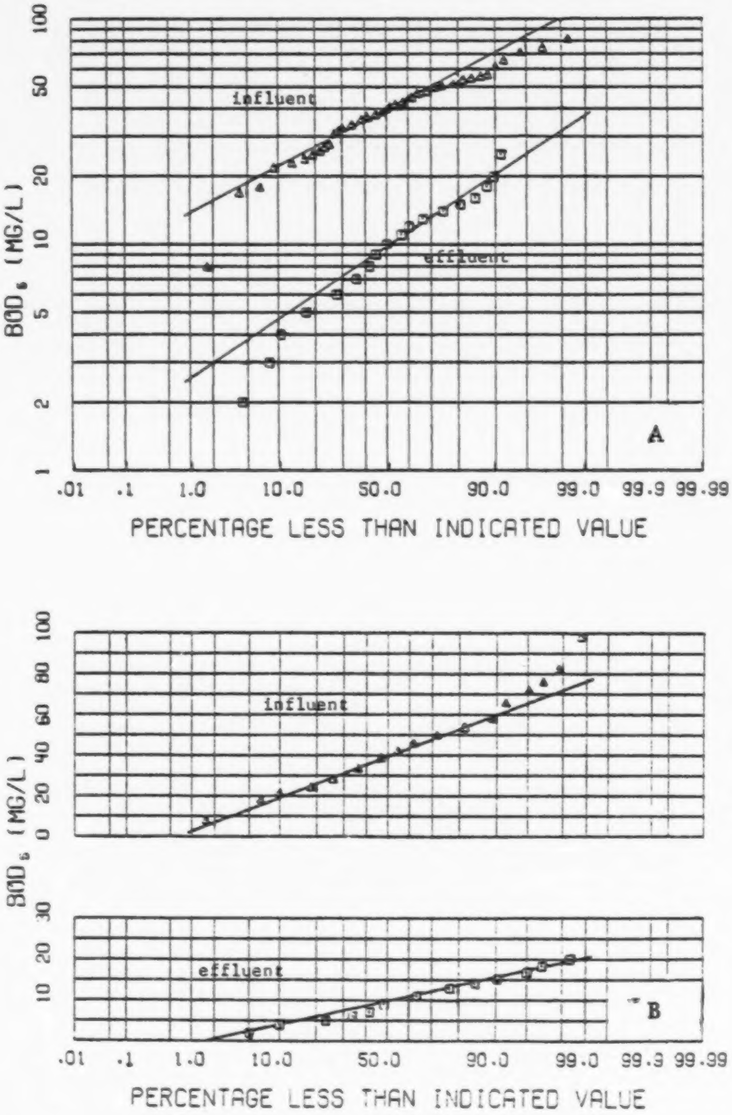


**Figure 13.** Cumulative frequency distribution of total BOD, Addison South plant.

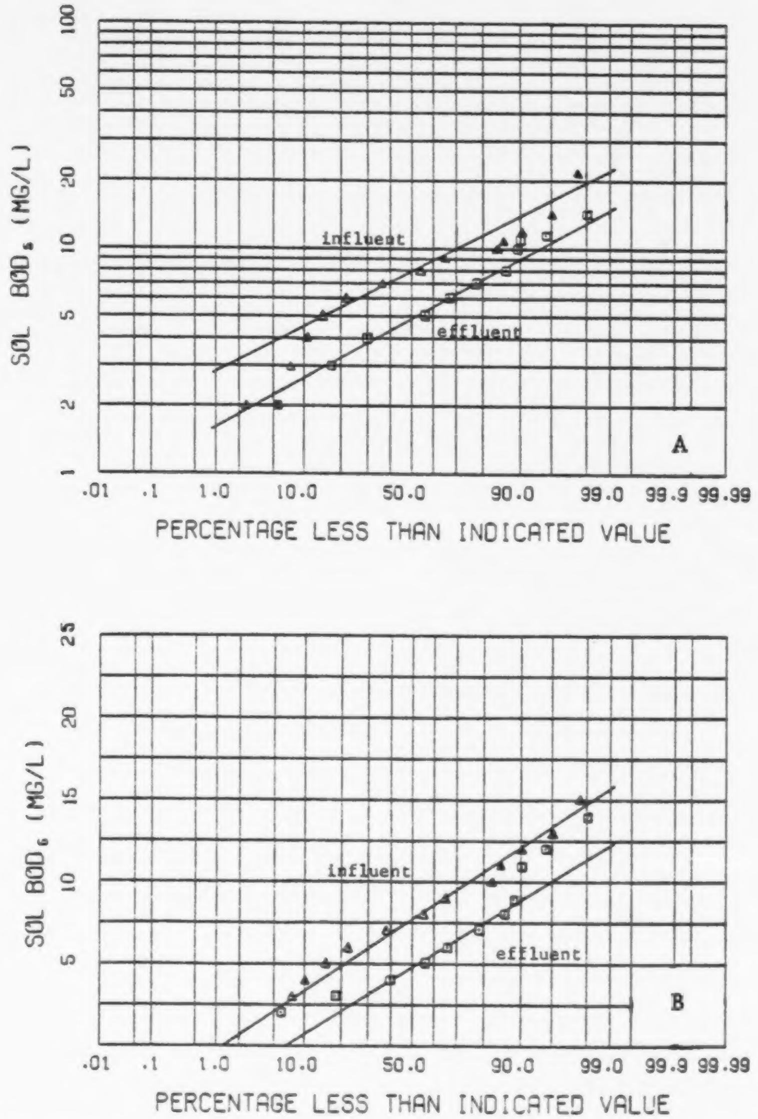


Table 14. Cumulative frequency distribution of soluble BOD, Addison South plant.

Table 11. Goodness of fit summary, Addison North and South plants.

| | LOG NORMAL | | | NORMAL | | |
|---|---|---|---|---|---|---|
| Parameter | K-S* | CHI-SQ+ | PLOT | K-S* | CHI-SQ+ | PLOT |
| North Plant | | | | | | |
| Flow | .41 | | XX | .13 | | |
| $C_{ob}$ | .63 | .41(2) | X | .45 | .17(2) | |
| Sol.$C_{ob}$ | .86 | | | .63 | .40(2) | X |
| $C_b$ | .41 | | X | .05 | .50(2) | |
| Sol.$C_b$ | .18 | .20(2) | XX | .05 | .04(2) | |
| $C_o$ | .76 | .37(2) | X | .34 | | |
| C | .52 | .41(4) | X | .10 | .33(4) | |
| South Plant | | | | | | |
| Flow | .60 | .36(8) | X | .17 | | |
| $C_{ob}$ | .66 | .39(5) | | .89 | | X |
| Sol.$C_{ob}$ | .17 | .25(2) | | .22 | .50(2) | XX |
| $C_b$++ | .21 | .13(3) | | .29 | .10(3) | X |
| Sol.$C_b$ | .52 | .45(2) | X | .07 | | |
| $C_o$ | .81 | .42(3) | X | .24 | | |
| C++ | .74 | .03(2) | | .37 | .21(2) | X |

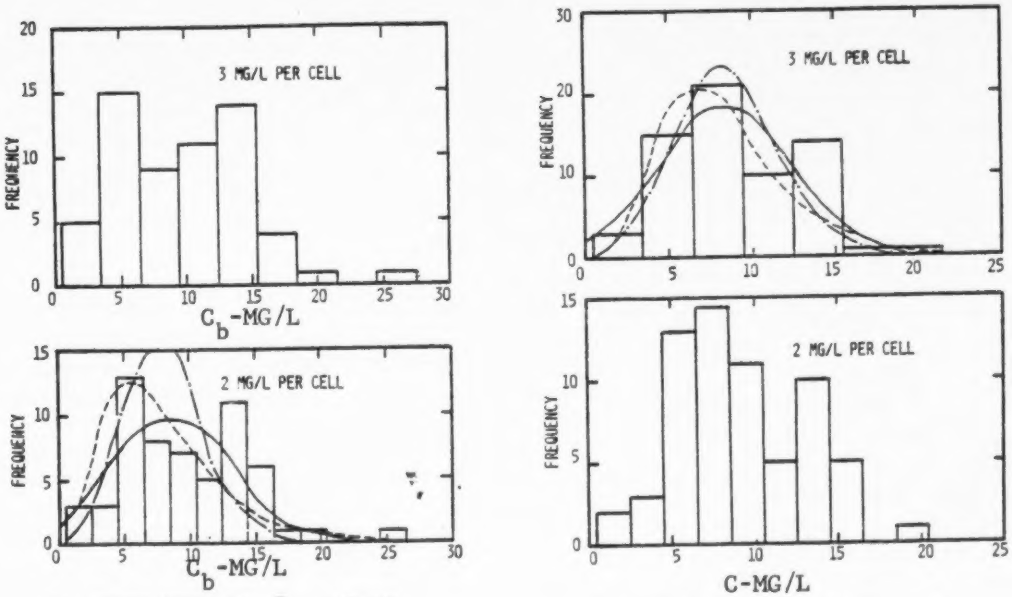
* Kolmogorov Smirnov (K-S) - 2 Tailed Test Significance Level.
+ Chi-squared test significance Level for degrees of freedom in parentheses.
++ Bimodal
X Good visual fit to line with same $\check{m}_x$ and $\sigma_x$ or $\sigma_{\ell nx}$
XX Better visual fit of two distributions, but still not very good.

soluble $C_{ob}$ for Addison South and North), a somewhat higher but still low significance fit for the Poisson distribution was obtained by the $\chi^2$ test. C at Addison South showed a weak fit (29 percent significance level). Soluble BOD parameters at both plants showed the best fit to the Poisson distribution (66 percent significance at 2 degrees of freedom for the South plant and 73 percent significance at 2 degrees of freedom at the North plant). In most instances, when a greater than 20 percent significance is recorded for both the K-S and Chi-squared test, the visual fit is in agreement. If the K-S and Chi-squared significance predictors are widely discrepant, the distribution showing the higher K-S significance corroborates the visual fit. These lines of observation may be seen by examining Table 11.

Relative frequency histograms of $C_o$ and $C_{ob}$ data for the North and South plants are presented in Figure 15. This figure helps, to some extent, to interpret the results given in Table 11. By and large, the data that fall in the tails of the distributions are most important in determining the goodness of fit, and those data sets that show a reasonable fit of the tails on the appropriate probit plot corroborates whether the fit is better to normal or log normal statistics. In two cases in particular, this seems not to be followed: for the North Plant total $C_b$ and C are concluded to show a better fit to the log normal distributions although relatively significant Chi-squared values were obtained. This may be explained by looking at the frequency histogram on Figures 15C and 15D. Both are skewed to the right. The absence of observations at negative values of the parameters result in comparing observed and expected frequencies for the normal distribution only in the range where agreement is good. Thus the resulting Chi-squared value tends to be abnormally small and the corresponding significance of fit is too high. In this case the fit to a normal distribution has 50 percent significance at 2 degrees of freedom for total $C_b$ and 33 percent significance at 4 degrees of freedom for C.

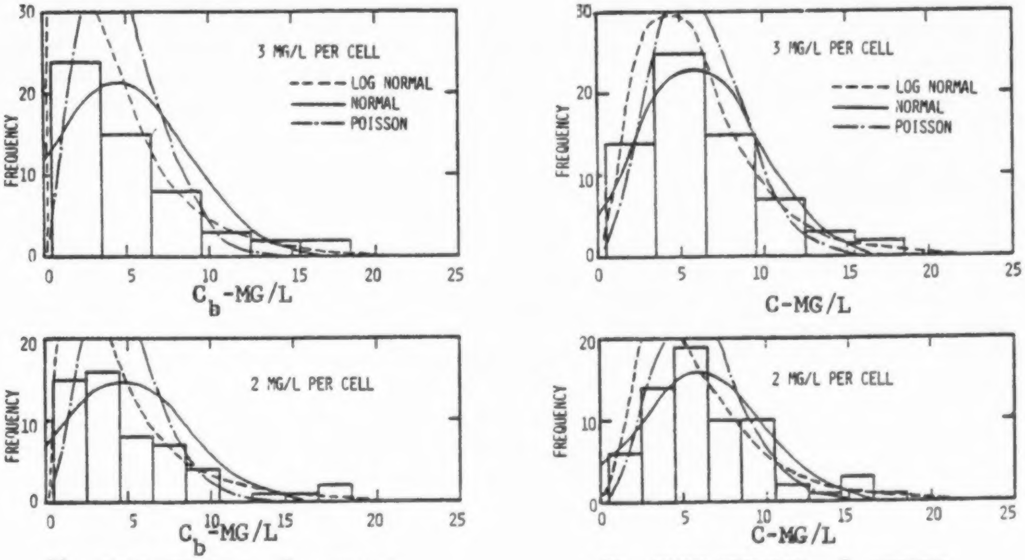
## Bimodal Distributions

Filter effluent data for Addison South show generally poor fit to either normal or log normal statistics. This is because both of these distributions appear bimodal, as shown in Figures 15A and 15B. To test the hypothesis that the data are bimodally distributed, the data were truncated with the aid of collateral data, i.e., data other than the parameters to be examined were cut at a given level. Corresponding filter effluent data were truncated according to chronology of data (several different ways) or mean values of process flow (Q), solids and BOD loading ($C_oQ$ and $C_{ob}Q$) and $C_b$ and C levels. Strongest evidence that the bimodal character is the combination of two unimodal distributions derives from truncation of $C_{ob}$ and $C_o$ data at their mean values. First mode C and $C_b$ appear to be associated with respective values of $C_o$ and $C_{ob}$ at less than their mean values. Likewise, second mode C and $C_b$ are associated with respective $C_o$ and $C_{ob}$ at greater than their mean values. In general, the number of data were insufficient to permit meaningful quantitative goodness of fit tests on the truncated distributions. Furthermore, simple bivariate correlation coefficients of $C_b$ and $C_{ob}$ (0.53) and C with $C_o$ (0.38) do not provide sufficient information to assess whether $C_{ob}$ and $C_o$ are the dominant determinants of tertiary effluent parameters for the South Plant.



(A) ADDISON SOUTH PLANT - $C_b$ HISTOGRAM

(B) ADDISON SOUTH PLANT - C HISTOGRAM



(C) ADDISON NORTH PLANT - $C_b$ HISTOGRAM

(D) ADDISON NORTH PLANT - C HISTOGRAM

Figure 15. Relative frequency distributions for $C_b$ and C, Addison North and South plants.

An attempt to fit the data to a bimodal distribution might be tried with a three parameter empirical model developed for particle size analysis and used in coagulation studies (Dallavalle, et al., 1951). The frequency distribution would then be given by an equation similar to those shown in Table 12. Several methods indicated in Table 12 could be used to evaluate the parameters, but many more data than the 60 or 70 we obtained would be needed to obtain a good fit. It must be stressed that the distribution so derived would be completely empirical and without any relation to the moments of the data.

## STATISTICAL ANALYSES FOR ALL PHASE 1 DATA

A summary of simple statistics for all Phase 1 data is given in Table 13. For the variable flow plants, statistical analyses were conducted using raw sewage flow rather than filtration rate. The results from statistical analyses for plants other than Addison North and Addison South must be interpreted with caution because data were not obtained during process upsets or when the filters were not in operation because of high flow. If data had been taken during these periods, it could be expected that a better fit would be obtained for the log normal distribution. A chronological summary of the sampling program is given in Table 4.

Data for Barrington, Des Plaines River, Marionbrook and Romeoville were obtained during two or more seasons of the year. From Table 13, the high coefficient of variation for flow for the Des Plaines River and Marionbrook can be attributed in part to seasonal variations. The high coefficient for C of 0.79 for Marionbrook suggests that particle collection mode may have changed during the study. For several plants, the coefficient of variation was higher for C than for $C_o$. Again, this suggests possible changes in particle collection mode during the sample period. The high coefficients of variation for $C_b$ of 0.79 and 1.1 for the Addison North and Des Plaines River plants, respectively, may be caused by the accuracy of the BOD test since effluent BOD is very low.

### Kolomogorov-Smirnov Tests

A summary of K-S goodness of fit data for the normal and log normal distributions for all Phase 1 plants is shown in Table 14. Data are not shown for the Poisson distribution which gave a very poor fit. For plants where flow was varied to individual filters, K-S and autocorrelation tests were made only for flow data from 24-hour runs. Tests for other parameters were made using all data. Insufficient BOD data (less than 20) were obtained for the variable flow studies at Addison South, Lisle, and Marionbrook plants for statistical analyses.

The 1975 Addison South flow data show a higher significance for the normal as compared to the log normal distribution, the opposite result obtained for the 1976 data. Sampling periods for each data set cover approximately the same months. Similar results were obtained in 1975 as compared to 1976 for $C_o$ and C, with the log normal distribution providing a better fit.

The Barrington and Lisle data show a good fit for flow to both distributions. The flow data for the Des Plaines River, Lake Zurich, and Marionbrook plants do not show a good fit for either distribution. As discussed

Table 12. Empirical Fit of Bimodal Data

$$\text{Frequency} = \exp\left[\left(- a_4\ x^4 + a_3\ x^3 + a_2\ x^2 + a_1\ x\ a_o\right)\right]$$

$$\text{or Frequency} = k\ \exp\left[\left(- a^2\ x^4 + p\ x^2 + q\ x\right)\right]$$

$$\text{where} \quad k = \exp\left[- ar^2\right]$$

The parameters a, p, q and k may be obtained by the 1) method of moments, 2) least squares method or 3) five ordinate method.

Table 13. Summary of simple statistics - Phase 1 data.

| Plant | No. of Cases | Flow[1] | | $C_{ob}$-mg/ℓ | | $C_b$-mg/ℓ | | $C_o$-mg/ℓ | | C-mg/ℓ | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | M[2] | CV[3] | M | CV | M | CV | M | CV | M | CV |
| Addison North | 73 | 3.8 | .16 | 34 | .37 | 5.1 | .79 | 44 | .43 | 6.6 | .56 |
| Addison South-76 | 70 | 2.1 | .22 | 42 | .41 | 9.7 | .50 | 38 | .45 | 9.0 | .43 |
| Addison S.-77, Low Q | 61 | | | | | | | 52 | .42 | 11 | .65 |
| Med Q | 51 | 1.6 | .24 | | | | | 49 | .43 | 14 | .57 |
| High Q | 64 | | | | | | | 51 | .43 | 20 | .60 |
| Barrington | 58 | 3.6 | .23 | 37 | .35 | 16 | .36 | 37 | .32 | 12 | .34 |
| Des Plaines R. | 60 | .76 | .39 | 34 | .63 | 3.3 | 1.1 | 31 | .61 | 5.0 | .60 |
| Lake Zurich - Low Q | 24 | | | | | | | 28 | .39 | 9.5 | .31 |
| Med Q | 48 | .49 | .21 | 23 | .55 | 16 | .25 | 31 | .35 | 14 | .31 |
| High Q | 22 | | | | | | | 29 | .38 | 15 | .25 |
| Lisle - Low Q | 32 | | | | | | | 62 | .61 | 9.0 | .51 |
| Med Q | 29 | 3.0 | .17 | | | | | 59 | .61 | 12 | .62 |
| High Q | 35 | | | | | | | 61 | .61 | 18 | .72 |
| Marionbrook - Low Q | 105 | | | | | | | 38 | .53 | 7.1 | .76 |
| Med Q | 100 | 3.1 | .30 | | | | | 34 | .50 | 8.4 | .79 |
| High Q | 55 | | | | | | | 32 | .59 | 7.2 | .64 |
| Romeoville | 36 | 1.5 | .26 | 39 | .53 | 13 | .33 | 31 | .55 | 7.4 | .50 |

(1) For variable flow plants units are mgd. For non-variable flow plants units are gpm/sf

(2) arithmetic mean (3) coef. of variation

Table 14. Kolmogorov-Smirnov goodness of fit summary - Phase 1.

| Plant | No. Cases | K-S 2-Tailed Test Significance Level | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Flow** | | $C_{ob}$ | | $C_b$ | | $C_o$ | | C | |
| | | N* | L* | N | L | N | L | N | L | N | L |
| Addison North | 73 | .13 | .41 | .44 | .63 | .05 | .41 | .34 | .76 | .10 | .52 |
| Addison South-76 | 70 | .17 | .60 | .89 | .66 | .23 | .21 | .24 | .81 | .37 | .74 |
| Addison S.-75, Low Q | 61 | - | - | | | | | .03 | .46 | .07 | .74 |
| Med Q | 51 | .73 | .46 | | | | | .08 | .73 | .14 | .53 |
| High Q | 64 | | | | | | | .03 | .46 | .05 | .80 |
| Barrington | 58 | .82 | .88 | .56 | .28 | .06 | .39 | .80 | .18 | .62 | .72 |
| Des Plaines River | 60 | 0 | .02 | .19 | .44 | 0 | .60 | .43 | .88 | .76 | .77 |
| Lake Zurich, Low Q | 24 | - | - | | | | | .73 | .84 | .13 | .28 |
| Med Q | 48 | .11 | .34 | .04 | .50 | .72 | .62 | .18 | .80 | .40 | .33 |
| High Q | 22 | - | - | | | | | .34 | .74 | .65 | .63 |
| Lisle - Low Q | 32 | | | | | | | .19 | .68 | .08 | .63 |
| Med Q | 29 | .77 | .82 | | | | | .46 | .99 | .90 | .34 |
| High Q | 35 | | | | | | | .14 | .74 | .39 | .97 |
| Marionbrook - Low Q | 105 | | | | | | | .01 | .83 | .01 | .99 |
| Med Q | 100 | .25 | 0 | | | | | .03 | .49 | .08 | .29 |
| High Q | 55 | | | | | | | .05 | .87 | .19 | .77 |
| Romeoville | 36 | .96 | .71 | .16 | .50 | .67 | .04 | .02 | .25 | .07 | .54 |

* N-Normal, L- Log Normal
** Based on raw sewage flow for variable flow plants.

earlier, those plants were not always sampled during process upsets and high flow periods.

The secondary effluent and filter effluent BOD data are about equally split between providing better fits to the normal as compared to the log normal distributions. Except for the Barrington plant, all data sets provide a better fit for $C_o$ to the log normal distribution. Ten of the 17 data sets for C show higher significance for the log normal distribution; five are about equal and two show a better fit for the normal distribution. In addition, the C data show a better fit for lower values of the coefficient of variation.

## Extent of Autocorrelation

In autocorrelation tests, the time interval lag must be selected. Autocorrelation coefficients are shown in Table 15 for a time lag of one composite sample period. For an interval of one, it would be expected that $r_a$ would be positive unless a change occurred in the operating mode. In general, Q shows the highest autocorrelation as would be expected because of seasonal changes during the sampling periods caused by variations in sewer system infiltration and inflow. From Table 15, influent and effluent BOD have the lowest autocorrelation.

A plot of daily changes in C and $C_o$ for the Addison South Plant is shown in Figure 16. The values of $r_a$ are 0.34 and 0.20 for C and $C_o$, respectively. Figure 16 shows a decreasing trend for both C and $C_o$. The decrease in $C_o$ can be attributed in part to the decrease in plant flow ($r_a$=.58) and increase in efficiency of the final sedimentation tanks during the sampling period. The values of $r_a$ for C and $C_o$ for other plants were generally less than 0.6.

It can be concluded that the extent of autocorrelation is low enough so that the basic assumption that the data are independent is reasonable.

## DISCUSSION

The results of the statistical tests to determine the best frequency distribution to use for these data were rather encouraging. It is clear that the Poisson and negative binomial distributions do not appear to offer any advantages for analysis of this type of data. What choice exists is between the normal and log normal distributions. If the spread of data is small, there is not much difference between these distributions. For most sets of data, the log normal distribution should give a better fit because the logarithmetic transformation greatly condenses the range of the data.

The results of the $\chi^2$ and K-S tests did show a clear cut preference for the log normal distribution for all parameters at Addison North except soluble $C_b$. This may reflect a more stable operation at the North plant. Based on $\chi^2$ and K-S tests, the South plant data appear split between normal and log normal statistics. However, closer examination shows that two of the parameters $C_b$ and C are bimodal distributions and not really best fit by the normal distribution. Therefore, the log normal distribution appears to fit the same parameters at the South as the North plant, excluding the two that are bimodal. No explanation is offered as to why soluble $C_b$ should be the only parameter with a better fit to the normal than log normal distribution.

Table 15. Autocorrelation coefficients - Phase 1.

| Plant | No. of Cases | $Q^*$ | $C_{ob}$ | $C_b$ | $C_o$ | $C$ |
|---|---|---|---|---|---|---|
| Non-Variable Flow | | | | | | |
| Addison North | 73 | .69 | .09 | .17 | .48 | .23 |
| Addison South | 70 | .58 | .05 | .03 | .20 | .34 |
| Barrington | 58 | .54 | .29 | .11 | .07 | .30 |
| Des Plaines R. | 60 | .13 | .13 | .26 | .37 | .21 |
| Romeoville | 36 | .54 | .35 | .02 | .36 | .25 |
| Variable Flow | | | | | | |
| Addison South | | | | | | |
| Low Q | 61 | | -.02 | - | .51 | .54 |
| Med Q | 51 | .72 | -.04 | -.02 | .52 | .31 |
| High Q | 64 | | .20 | .35 | .53 | .54 |
| Lake Zurich | | | | | | |
| Low Q | 24 | - | - | - | .36 | .59 |
| Med Q | 48 | .34 | .26 | .20 | 0 | .02 |
| High Q | 22 | - | - | - | .51 | .05 |
| Lisle | | | | | | |
| Low Q | 32 | - | - | - | .21 | .67 |
| Med Q | 29 | .52 | - | - | .53 | .55 |
| High Q | 35 | - | - | - | .24 | .80 |
| Marionbrook | | | | | | |
| Dry Weather- Jan-Feb.'76 | | | | | | |
| Low Q | 21 | - | - | - | .52 | .60 |
| Med Q | 31 | - | - | - | .57 | .52 |
| 1st half Wet Weather - | | | | | | |
| Low Q | 38 | - | - | - | .25 | .43 |
| Med Q | 24 | .04** | - | - | .14 | .40 |
| High Q | 26 | - | - | - | .06 | .44 |
| 2nd half Wet Weather - | | | | | | |
| Low Q | 41 | - | - | - | .35 | .21 |
| Med Q | 32 | - | - | - | .37 | .03 |
| High Q | 16 | - | - | - | .19 | .16 |

*Based on raw sewage flow for variable flow plants

**Based on all data

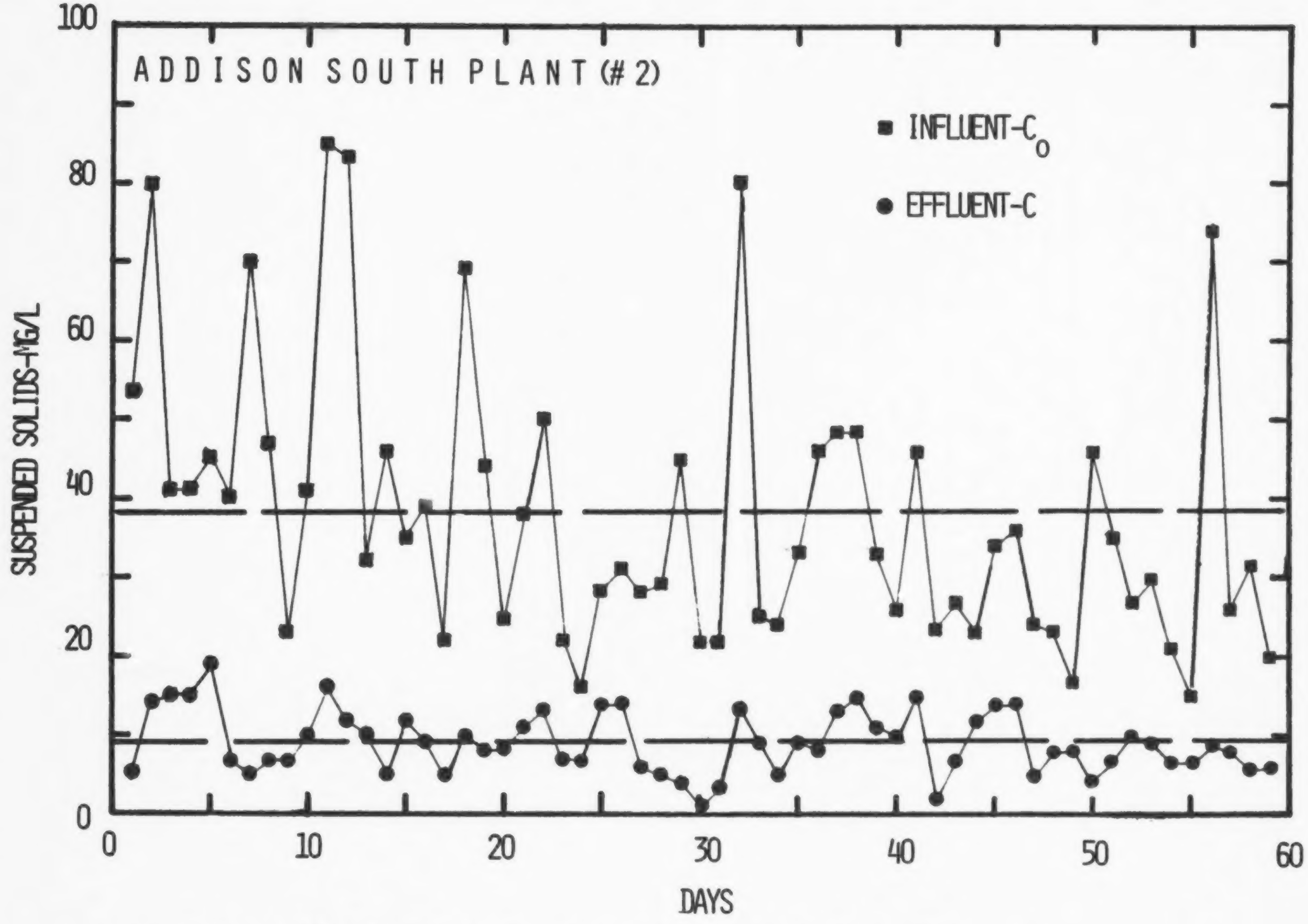


Figure 16. Daily changes in C and $C_o$, Addison South Plant (#2).

The distribution of effluent quality parameters is the result of complex interactions among a number of factors. It seems reasonable to assume that if the flow rate, wastewater strength, and operating conditions were about the same for several days, the effluent quality should be about the same for that period of time. "About the same" in this context means that small variations from day to day will make the effluent quality parameters slightly higher or slightly lower than the average values. This suggests that over short periods of time, the effluent quality parameters should have normal distributions.

Wastewater flow and strength and operating conditions do not remain "about the same" for very long. A rainfall will change many factors, seasonal temperature differences change the biota of the secondary treatment processes, and operational conditions change abruptly due to many occurrences such as digester upsets, failure of mechanical equipment, etc. An upset may occur for a short period of time producing one or two days of high effluent BOD and suspended solids. On the other hand, a change in conditions may persist a long enough period of time for the processes to stabilize and start producing "about the same" effluent quality from day to day. This line of reasoning suggests that over a long period of time, the effluent quality data would fit a series of normal distributions each having different means with perhaps a few extremely high values from upsets. Data from a series of normal distributions with different means very well could appear to have a log normal distribution (Aitchison and Brown, 1957).

From the parameters for a fitted theoretical distribution, the frequency and corresponding values of secondary effluent suspended solids can be determined directly. However, the particle collection mode for granular media filters may not be the same over the range of $C_0$. Thus it is not possible to calculate performance directly from the fitted distribution with a high degree of precision, although the models developed in Chapters VIII and X for in-depth filtration and straining can be used to estimate an expected range of effluent quality if suspension properties are known.

## CHAPTER VIII

## RELATIONSHIP OF FILTER CLARIFICATION EFFICIENCY TO CONVENTIONAL OPERATING PARAMETERS--PHASE 1 DATA

### INTRODUCTION

This chapter compares filter clarification efficiency with conventional parameters such as secondary plant operational variables, flow, influent solids concentration, influent solids loading, and filter media specifications. Operational mathematical models are developed and tested using data from Phase 1 of the study.

### RELATIONSHIP TO SECONDARY PLANT OPERATIONAL VARIABLES

Several of the operational variables used for design and control of the activated sludge process relate to some extent to the characteristics of mixed liquor suspended solids. The sludge volume index (SVI), defined as the volume in $m\ell$ occupied by 1 gm of solids after settling for 30 min., is a measure of the resistance of solids to thickening. The food to micro-organism ratio (F/M) is a measure of organic loading. F/M is defined as the ratio of BOD added per day to mixed liquor suspended solids under aeration.

Kreissl (1974) reported that for studies at the EPA Blue Plains Pilot Plant in Washington, D.C., both secondary effluent and dual media filter effluent suspended solids (SS) increased when SVI increased. Culp and Culp (1971) reported that higher effluent SS are expected for high F/M ratios.

Data on plant operational parameters were obtained from monthly reports to the State of Illinois and included raw sewage BOD, aeration tank suspended solids concentration, sludge volume index, and aeration tank dissolved oxygen concentration. Plots of C and $C/C_0$ vs. F/M and SVI are shown in Figures 17 and 18, respectively, for the Addison North and South plants. No correlation of filter performance with these plant operational variables is apparent. Multivariate correlations including filtration rate and filter solids loading yielded the same result and are not reported here. Mean values of plant operational variables and a bivariate correlation matrix with filter performance is given in Appendix A (Tables A-1 and A-2).

### ANALYSIS OF AVERAGE PERFORMANCE DATA

Plots of $\overline{C/C_0}$ vs. average flow rate ($\overline{Q}$) and average influent solids loading ($\overline{C_0Q}$) are shown in Figures 19A and 19B respectively, for plants where flow was varied to individual filters. Although the independent variables $C_0$ and

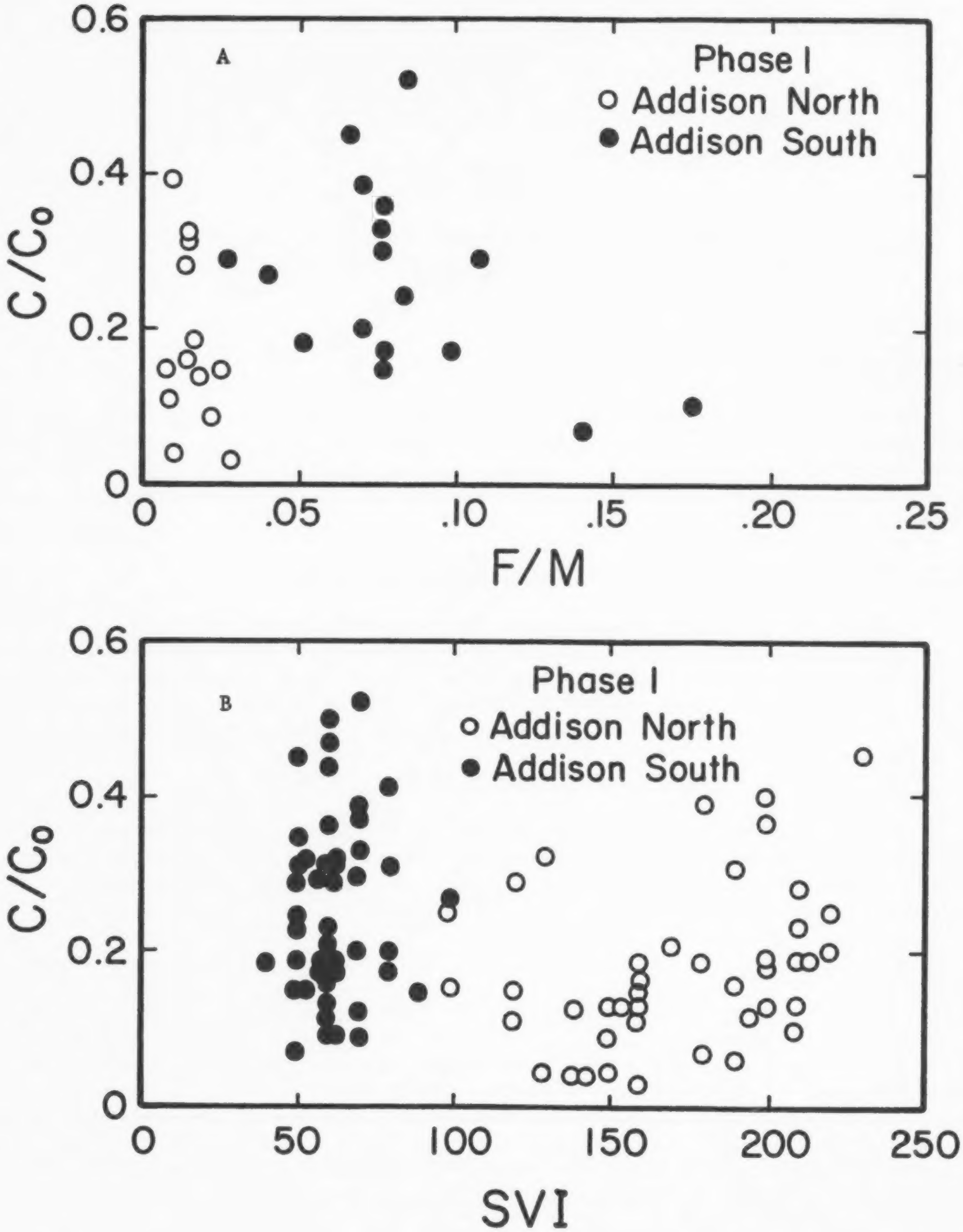


Figure 17. $C/C_o$ vs. food to microorganism ratio and sludge volume index, Addison North and South - Phase 1.

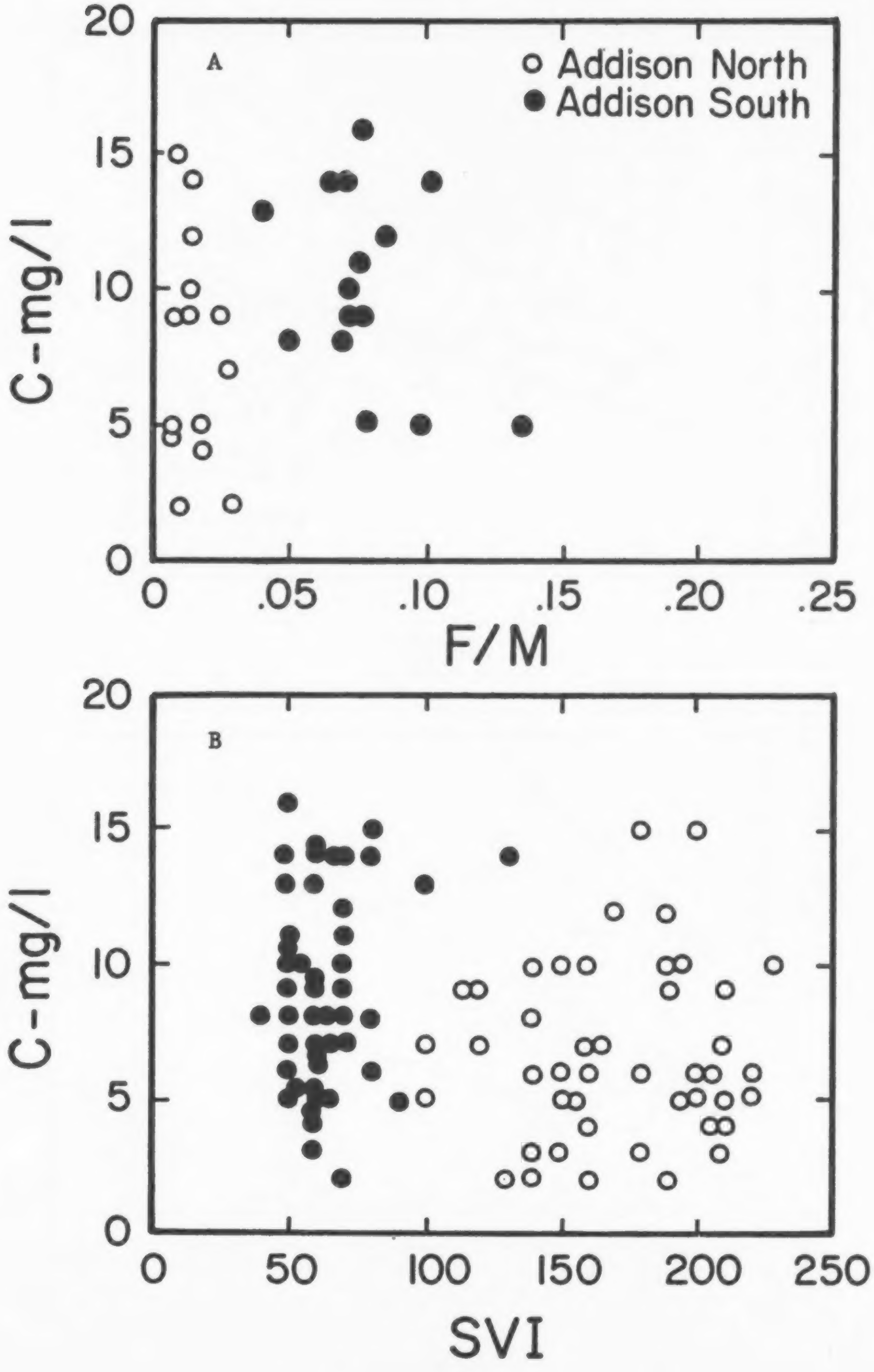


Figure 18. C vs. food to microorganism ratio and sludge volume index, Addison North and South - Phase 1.

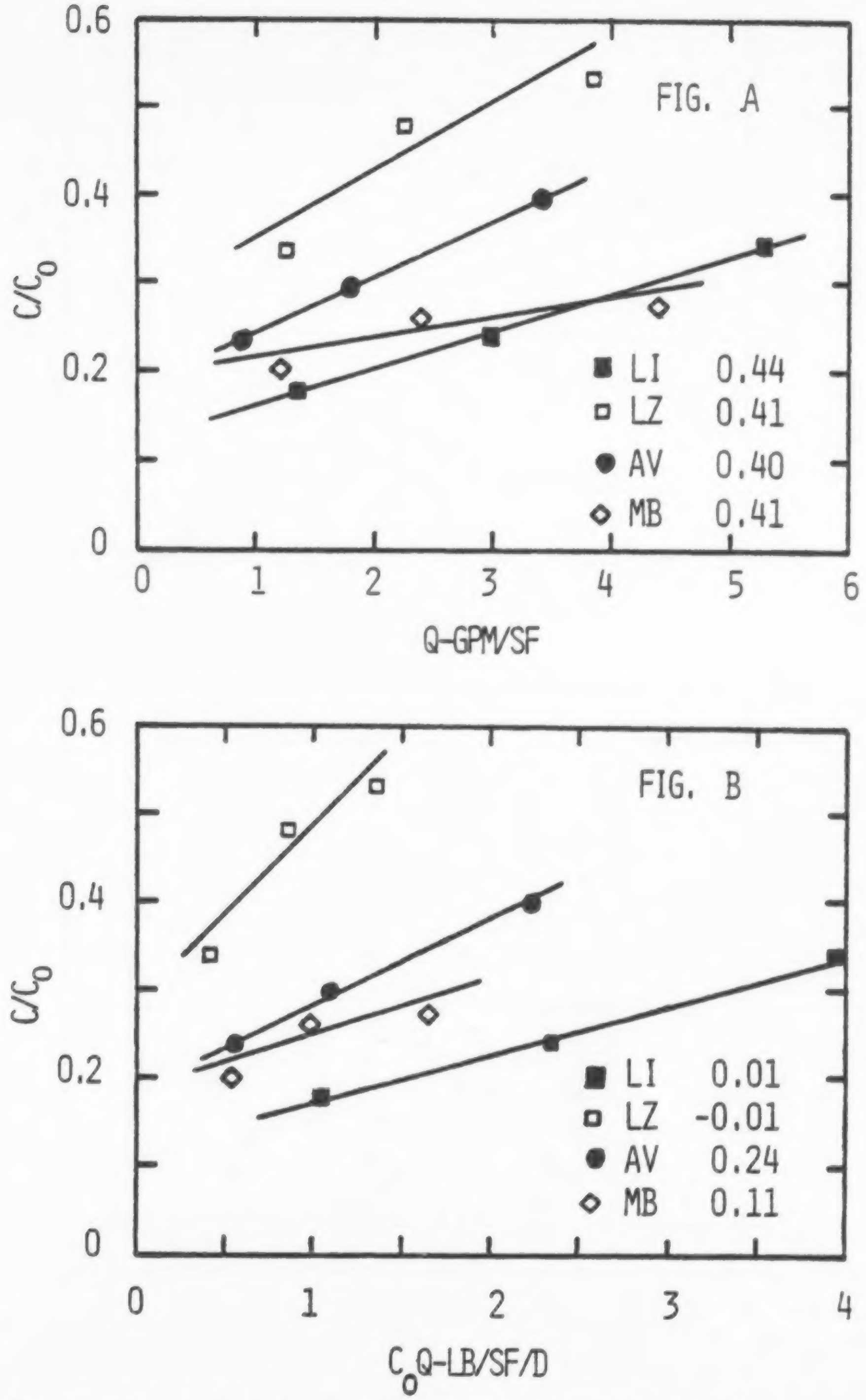


Figure 19. Ave. $C/C_o$ vs. ave. flow and solids loading.

Q varied widely, as did $C/C_o$, the average performance ($\overline{C/C_o}$) and effluent suspended solids ($\bar{C}$) appear linear with flow rate. For individual data, it is not possible for both relationships to be linear unless $C_o$ is constant and $\overline{C_o}$ is constant for each data point for Lisle and Addison South plants. For those plants, data were obtained for low, medium and high filtration rate simultaneously. The more nonlinear dependence apparent for the Lake Zurich (LZ) and Marionbrook (MB) plants may result from the fact that the three filters (low, medium and high rate) were not always in operation at parallel times and thus $\overline{C_o}$ is not constant for each.

Figures 20A and B show average effluent suspended solids ($\bar{C}$) as a function of flow and solids loading for the Addison South and Lisle plants. Data for the Lake Zurich and Marionbrook plants are excluded from this plot because $\overline{C_o}$ was not constant, as already mentioned. As with average data for $C/C_o$, a linear dependence of $\bar{C}$ with $\bar{Q}$ and $\bar{C}$ with $\overline{C_oQ}$ is apparent. Linear correlation coefficients for all pairs of data in each of the data sets is shown on Figures 19 and 20. The Addison plant (AV) shows highest ($r = 0.70$) correlation of C with $C_oQ$. Remaining data sets on Figure 20 show marginal correlation ($r = 0.55$) and some data sets in Figure 19 show no correlation individually, e.g., Lake Zurich and Lisle on Figure 20.

In this phase of the work, no routine quantitative measurements were made to determine particle size distributions. However, it was observed that the suspended solids for the Lake Zurich and Marionbrook plants secondary effluents were more finely divided compared to the other plants. This is not surprising since both plants have ponds ahead of tertiary filtration. The secondary processes for the Lake Zurich and Addison South plants consist of activated sludge and trickling filters in parallel. It would be expected that suspended solids in trickling filter plant effluents would be less flocculent compared to activated sludge plant effluents.

Interpretation on theoretical grounds (gravity settling and low hydrodynamic shear) suggests that performance ($1 - C/C_o$) should increase more than the linear relations suggested at low flow or solids loading. Even so, a finite intercept C or $C/C_o$ is expected at zero flow rate suggesting that a portion of the secondary effluent suspended solids cannot be removed by granular media filtration without alteration of suspension characteristics, e.g., particle size and charge by chemical addition. However, this point is academic since filters are only economic at higher flow rates.

Graphs of average $C/C_o$ as functions of average temperature, total media depth, and equivalent media diameter ($d_e$) are shown in Figures 21, 22A and B respectively, where $d_e$ is the equivalent media diameter ($d_{50}$) that would give the same clean bed headloss as the sand and anthracite media sizes at the same total depth. Values of $d_e$ were calculated from Kozeny's equation for flow through porous media, as shown in Appendix B. For plants where flow was varied, only data for the medium flow rates are shown.

If one excludes the single medium sand filters at the Des Plaines River (DP) and Romeoville (RO) plants, Figure 21 shows a strong dependence of filter performance on temperature (broken line) over the relatively narrow temperature range of $55^\circ$ to $67^\circ$F. It is believed that this is an artifact resulting

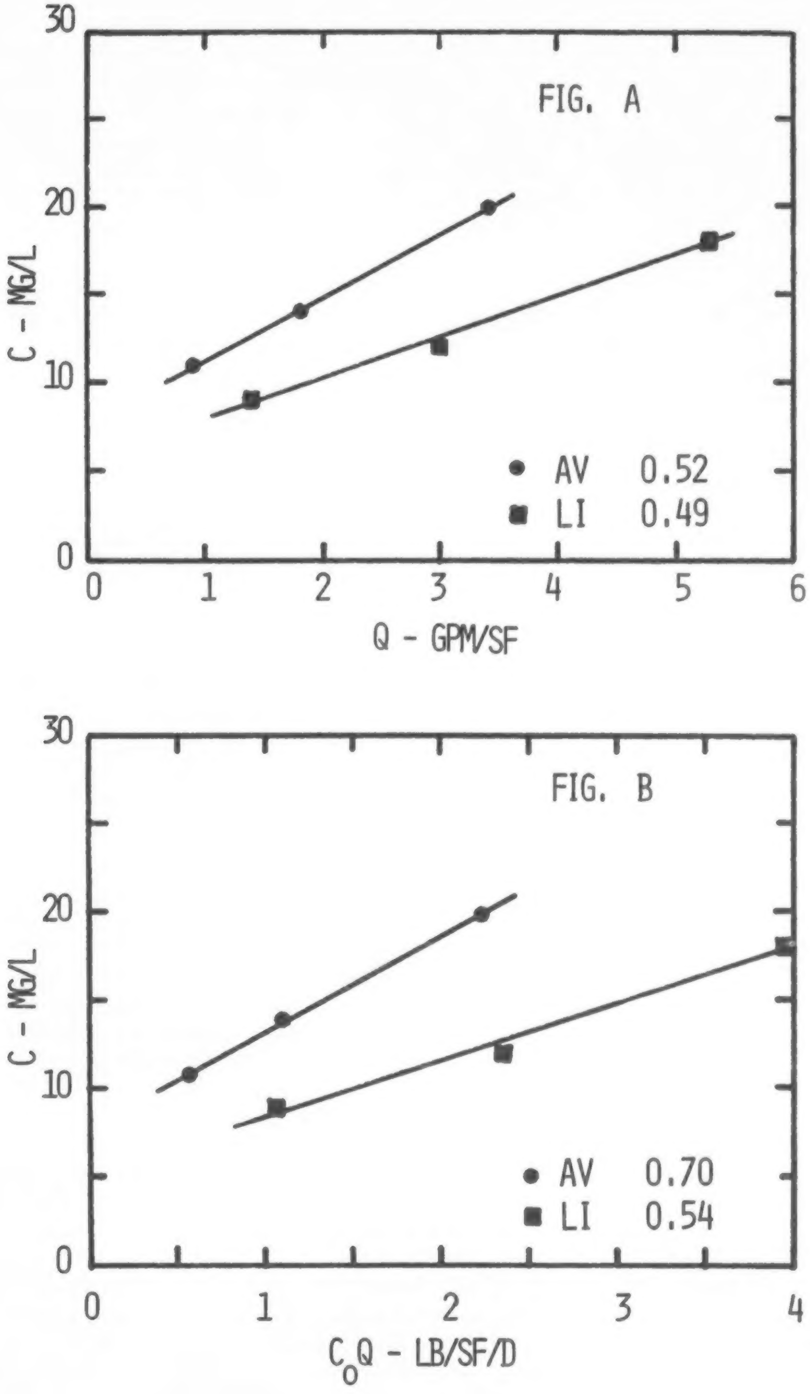


Figure 20. Ave. C vs. ave. flow and solids loading.

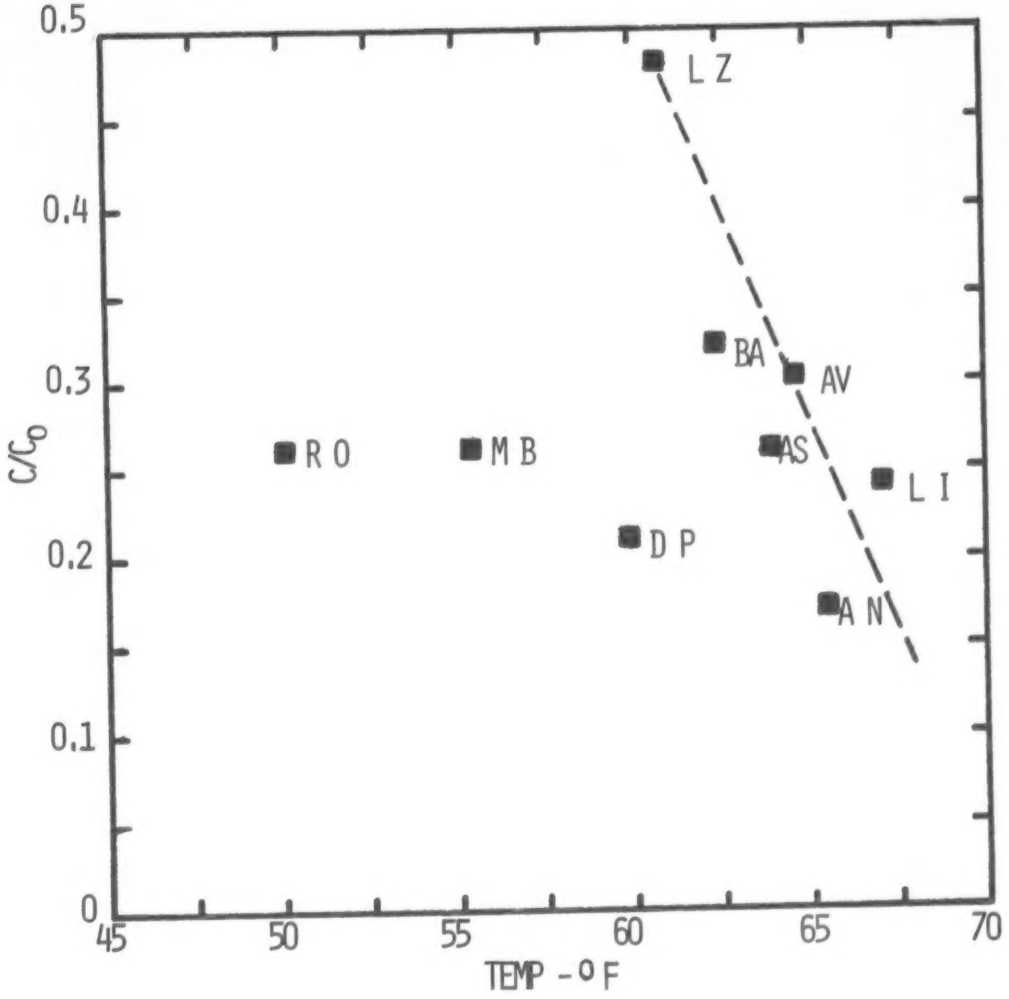


Figure 21. Ave. $C/C_o$ vs. ave. temperature.

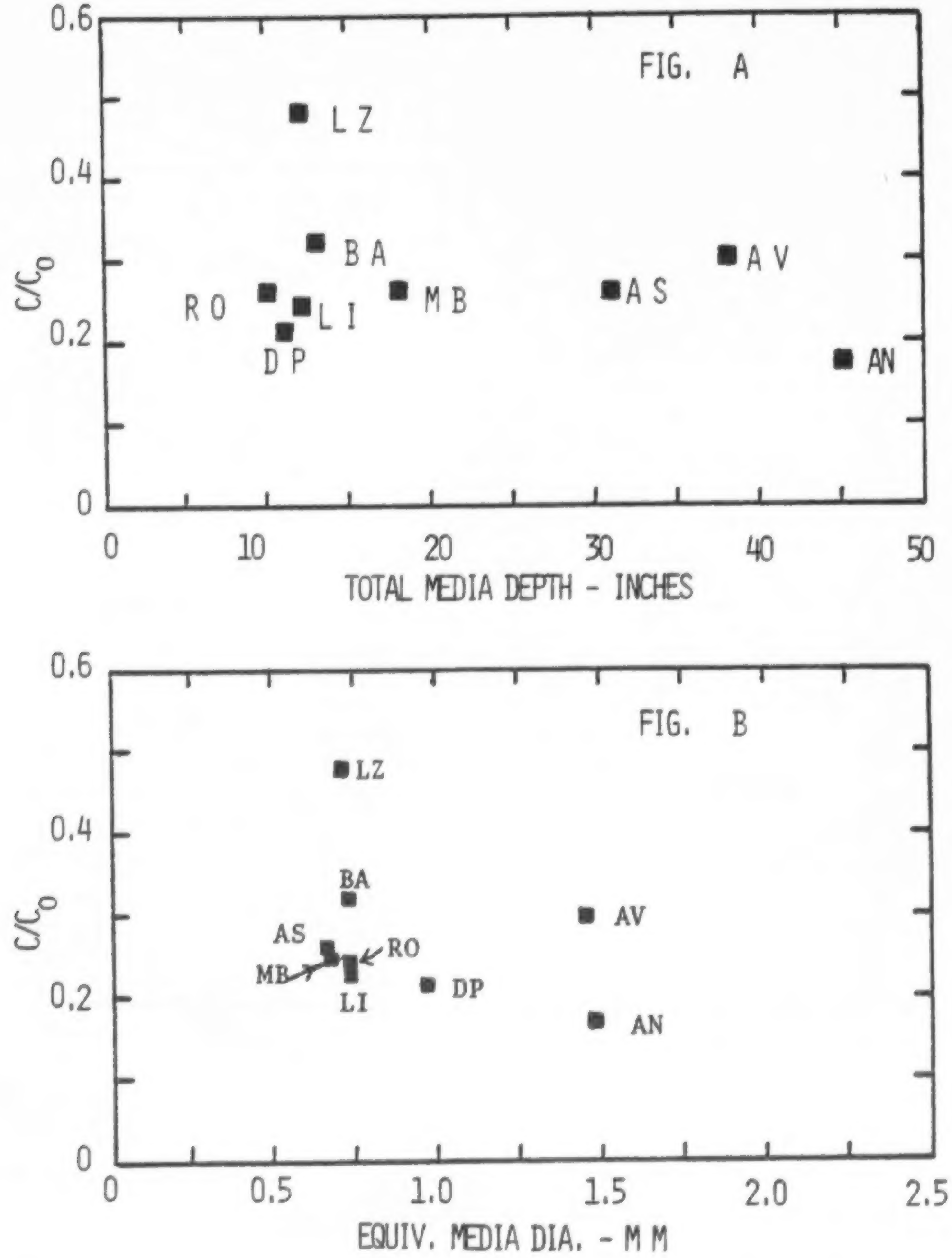


Figure 22. Ave. $C/C_o$ vs. media depth and equivalent media diameter.

from "chance" in the selection of plants and times of the year for sampling. Alternatively, if one realizes that the Lake Zurich and Addison North plants had the finest and coarsest particle size, respectively, in the filter influent, then their average $C/C_o$ ordinate is fixed basically on this factor. Eliminating those plants and realizing that other plants had comparable filter influent particle size, $\overline{C/C_o}$ is independent of water temperature.

If suspension properties are constant, an inverse dependence of performance on media depth would be expected if in-depth, rather than surface filtration, is the dominant particle collection mode. Surface cake and/or sieving filtration are believed to be the dominant modes for the sand filters at the Des Plaines River and Romeoville plants. If suspension properties are constant, higher removal efficiency should be obtained for finer media whether straining or depth filtration is operative. However, if the bulk of the removal is of coarse solids, little dependence of removal efficiency on media size or depth will be apparent, and residual suspended solids will be a relatively constant fraction of influent solids. With the information that the Lake Zurich and Addison North filter influent suspensions were coarsest and finest, respectively, for any plant tested, then Figures 23A and B show that average removal of the remaining plants (with comparable influent suspensions) is independent of media depth and equivalent media diameter.

## ANALYSIS OF INDIVIDUAL PLANT DATA

Bivariate correlation coefficients for plant performance and selected operating parameters are shown in Table 16. Although performance showed a strong correlation with flow and solids loading for average data where flow to individual filters was varied, much poorer correlations were obtained for individual data.

Correlation coefficients for C to $C_o$ varied from 0.18 to 0.71. Figures 23A and B show C as a function $C_o$ for the Addison South (Filter No. 2) and the Romeoville plants, respectively.

If solid breakthrough occurs before limiting headloss is exceeded or before filters are backwashed (manually or by timers), it would be expected that clarification efficiency would decrease with increasing run length. Except for the Lake Zurich plant, very poor linear correlations were obtained for C and $C/C_o$ with run length (RL). This is partly explained by the fact that the Lake Zurich filter influent had very fine suspended solids and fully developed depth filtration took place. Thus the active deposition zone (clogging front) advances through the filter with time giving rise to a breakthrough phenomena. Furthermore, run length was varied over a wider range for this plant compared to other plants where filters were manually backwashed at the start of a run. Also, the filter influent pumps at Lake Zurich cycled on and off, thus possibly providing a greater opportunity that solids could be sloughed from previous deposits and breakthrough experienced.

Except for plants where flow to individual filters was varied, linear correlation coefficients for C and $C/C_o$ to Q were less than 0.3. This suggests that, although flow is an important design parameter, day to day changes are too small compared to other variables, e.g., suspension properties, to result in measurable changes in filter performance. For plants where flow was varied

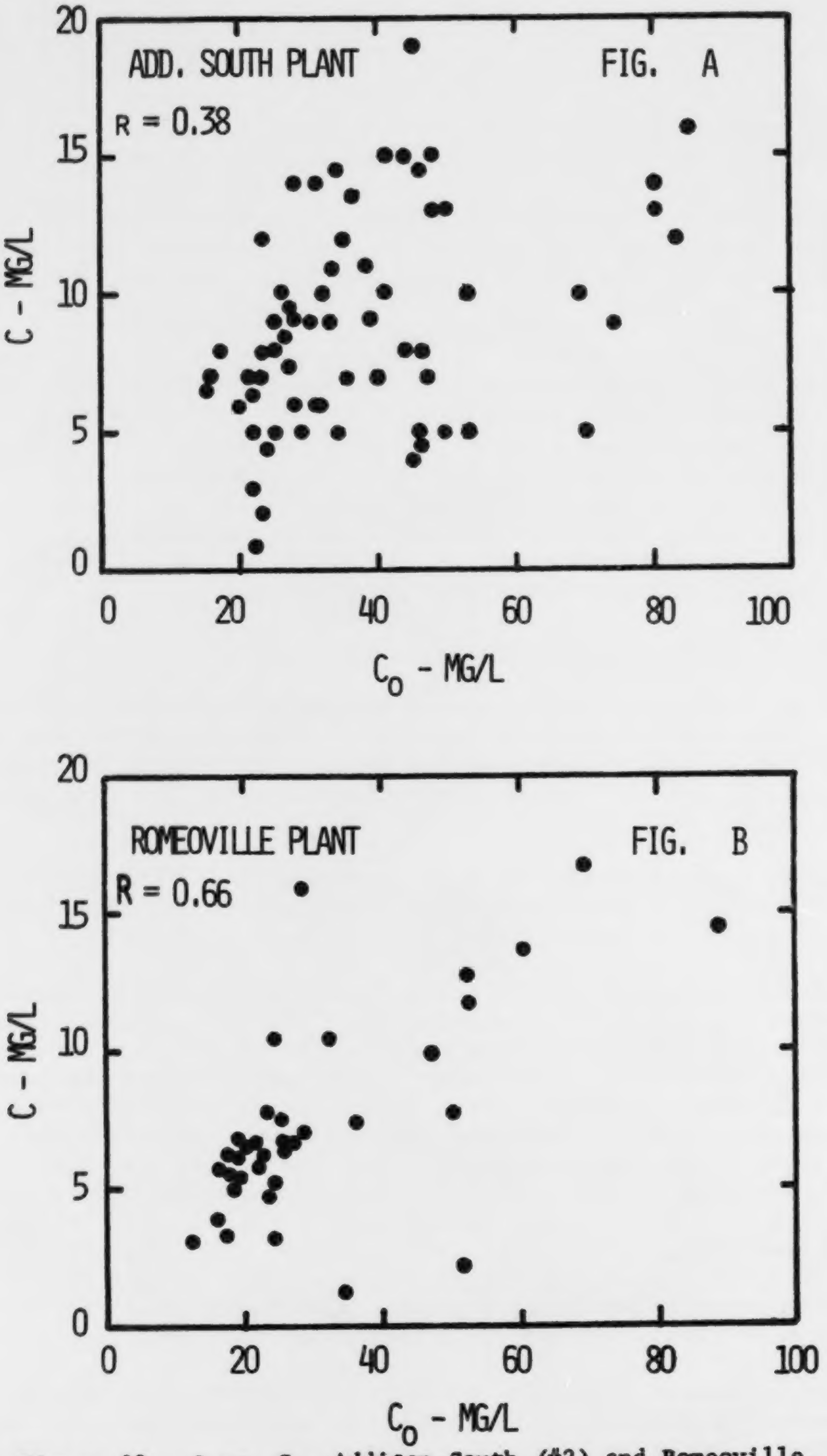


Figure 23. C vs. $C_o$, Addison South (#2) and Romeoville.

Table 16. Bivariate correlation coefficients for plant performance data - Phase 1.

| Plant | C to $C_o$ | C to Q | C to $C_oQ$ | C to RL | $C/C_o$ to Q | $C/C_o$ to $C_oQ$ | $C/C_o$ to RL |
|---|---|---|---|---|---|---|---|
| Addison North | .26 | .06 | .25 | -.05 | -.07 | -.41 | -.04 |
| Addison South (#2) | .38 | .02 | .31 | -.27 | .04 | -.47 | .22 |
| Addison S. (#4-7) | .48 | .52 | .70 | -.10 | .40 | .24 | -.01 |
| Barrington | .55 | .17 | .44 | .01 | -.27 | -.35 | -.15 |
| Des Plaines River | .37 | .33 | .45 | -.26 | -.10 | -.30 | .11 |
| Lake Zurich | .53 | .39 | .62 | 0 | .41 | -.01 | .18 |
| Lisle | .32 | .49 | .54 | .04 | .44 | .01 | .02 |
| Marionbrook | .40 | .26 | .49 | .10 | .41 | .11 | -.04 |
| Romeoville | .66 | -.02 | .68 | -.12 | .25 | .26 | .15 |

to individual filters, correlations for flow increased significantly for most data sets. A plot of $C/C_o$ vs. Q for the variable flow studies at the Addison South plant is shown in Figure 24.

A plot of $C/C_o$ vs. solids loading is shown in Figure 25 for the Lisle plant. No correlation of these two parameters is apparent. A similar result was obtained for other plants, as shown in Table 16, where bivariate correlation coefficients are less than 0.5.

The highest correlations of filter clarification efficiency were obtained for C vs. solids loading for the variable flow plants. Plots of C vs. $C_oQ$ are shown in Figures 26 to 29 for the Addison South, Lake Zurich, Lisle and Marionbrook plants, respectively. The data for the Marionbrook plant are for a period of dry weather flow early in the testing program where the correlation coefficient is 0.71. The Addison South data also show good correlation with a coefficient of 0.70. Wider scatter was obtained for the Lake Zurich and Lisle plants.

## TECHNIQUES FOR SEGMENTING INDIVIDUAL DATA SETS

The relatively poor correlations obtained between clarification efficiency and operating parameters can be attributed in part to other variables including characteristics of secondary effluent suspended solids and possible changes in the dominant particle collection mode during the sampling periods. In an attempt to improve correlations, data were segmented by: (a) a cumulative data analysis technique, (b) grouping by $C_o$ ranges, and (c) examining the relationship of solids capture to headloss increase.

### Cumulative Data Analysis

Since straining can be characterized by high headloss buildup and in-depth filtration by relatively lower headloss accumulation with time, cumulative plots of headloss or number of backwashes vs. time and solids loading may indicate when a change in particle collection mode occurs. These plots for the Addison North and South plants are shown in Figures 30 and 31, respectively.

From Figure 30, a marked point of inflection is apparent at the approximate midpoint of the test program for both the solids loading and time cumulative plots for the Addison North plant. Inflection points also occur for the Addison South plant in Figure 31 but are less pronounced. Backwash frequency is higher for the Addison North plant because of the higher flow rate.

Mean performance data and bivariate correlation coefficients for segmenting the Addison plant data into two time periods are shown in Table 17. During the first time period, flow and influent suspended solids concentrations were higher for both plants. No significant improvements in correlation of the data were obtained by use of this technique.

Plots of cumulative headloss vs. solids loading and time are shown in Figure 32 for the Marionbrook plant. If a filter backwashed during a run, the number of backwashes was multiplied by 6 ft. (maximum headloss) and added to the headloss at the end of the run to obtain total headloss. During the initial portion of the sampling program, headloss buildup was very low and in-

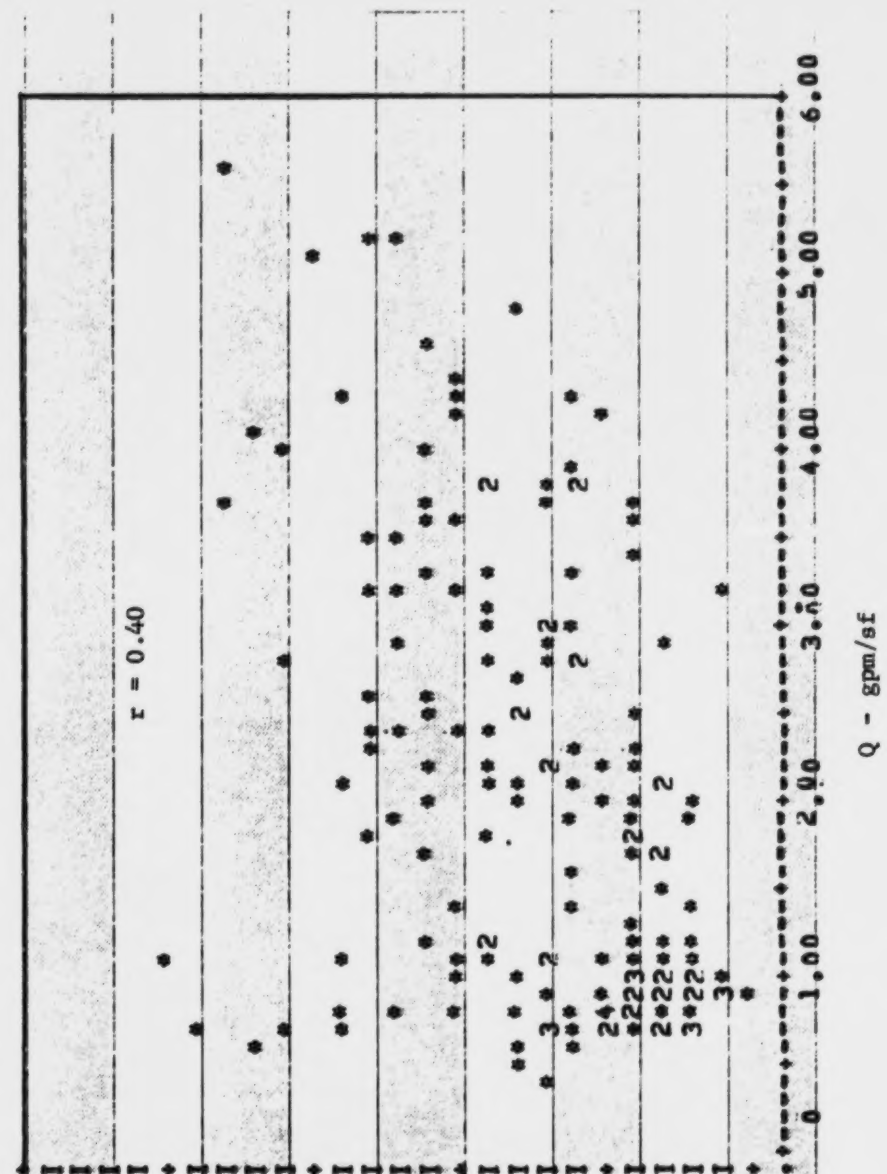


Figure 24. C/C$_o$ vs. flow rate, Addison South - Phase 1.

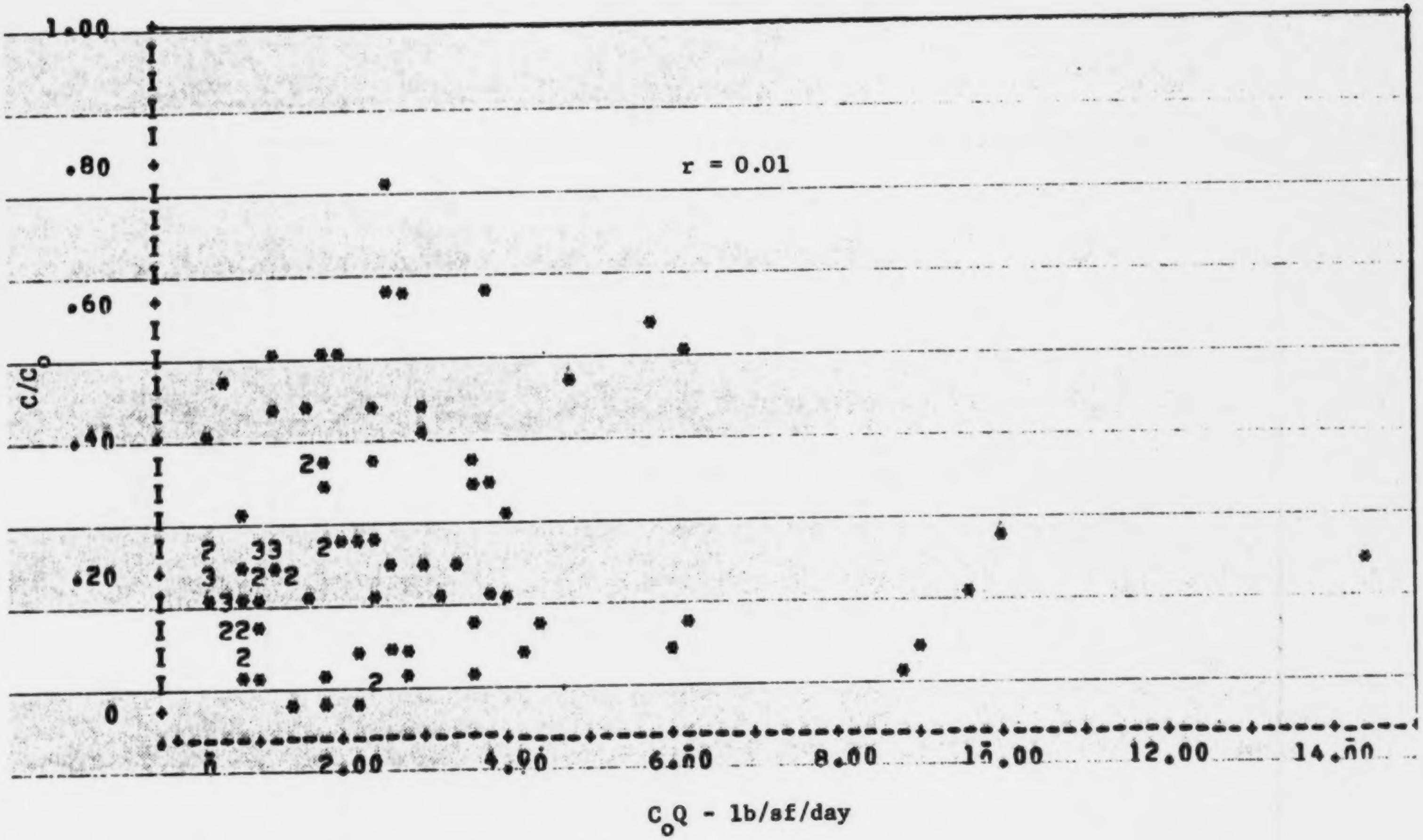


Figure 25. $C/C_o$ vs. solids loading, Lisle - Phase 1.

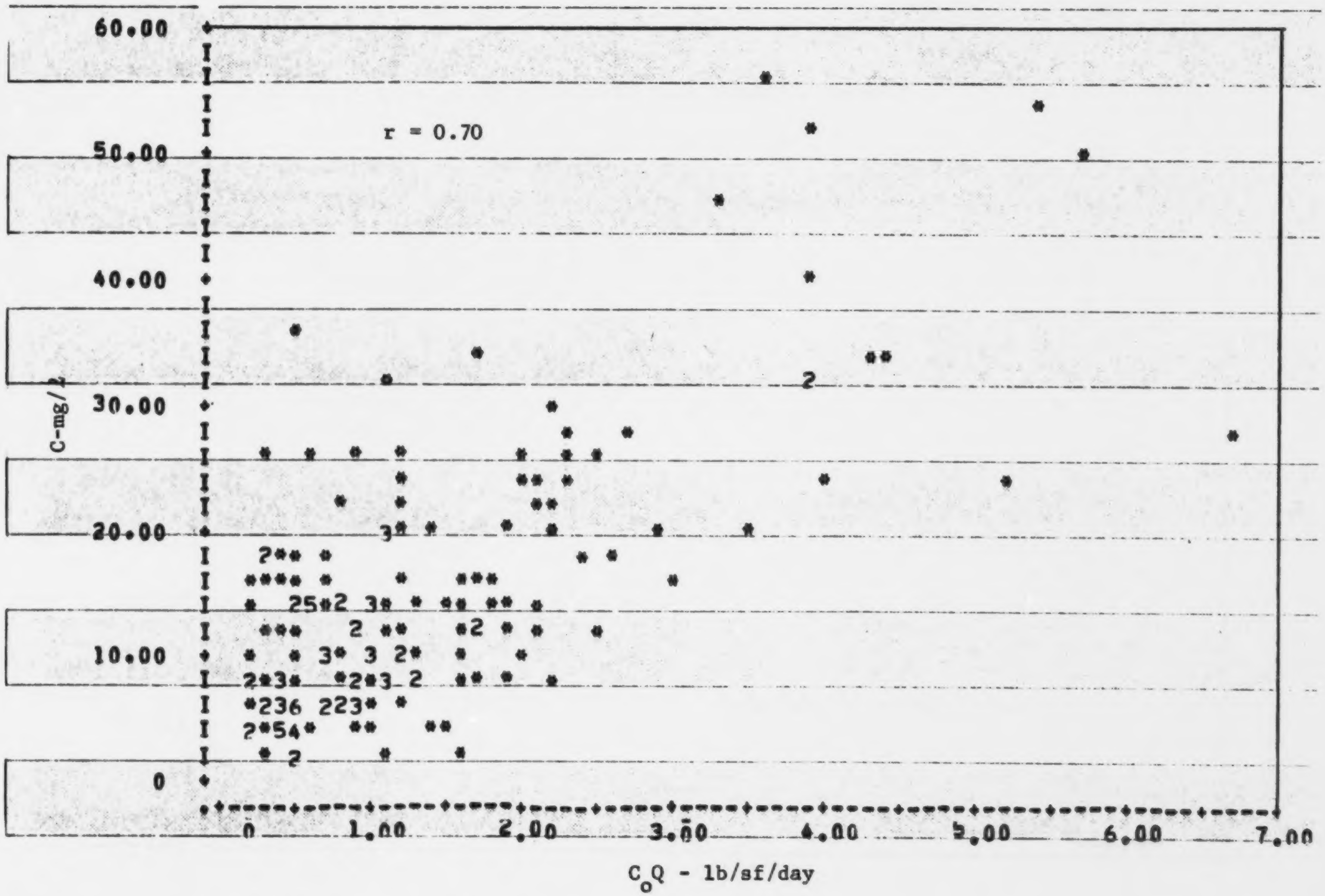


Figure 26. C vs. solids loading, Addison South - Phase 1.

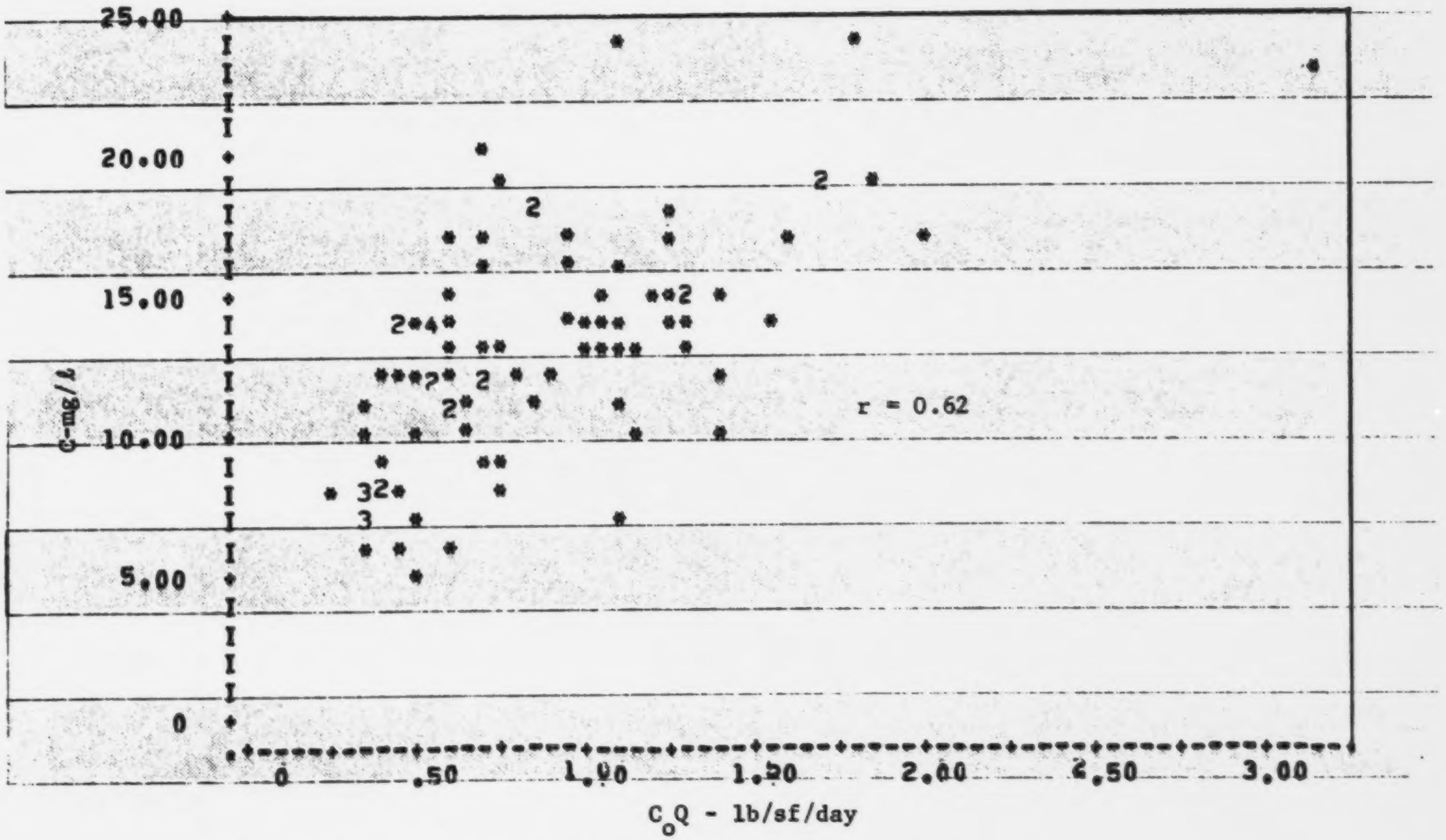


Figure 27. C vs. solids loading, Lake Zurich - Phase 1.

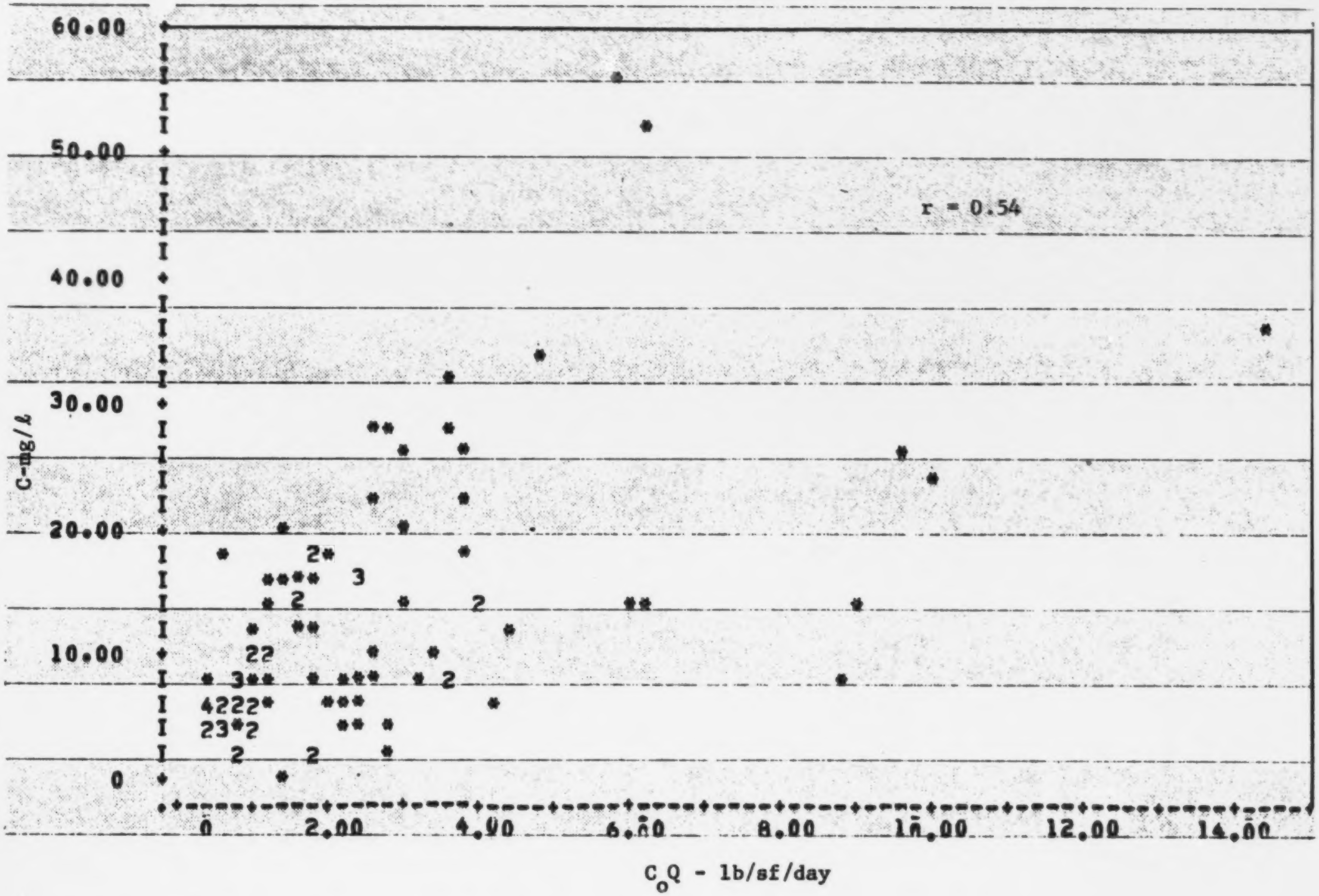


Figure 28. C vs. solids loading, Lisle - Phase 1.

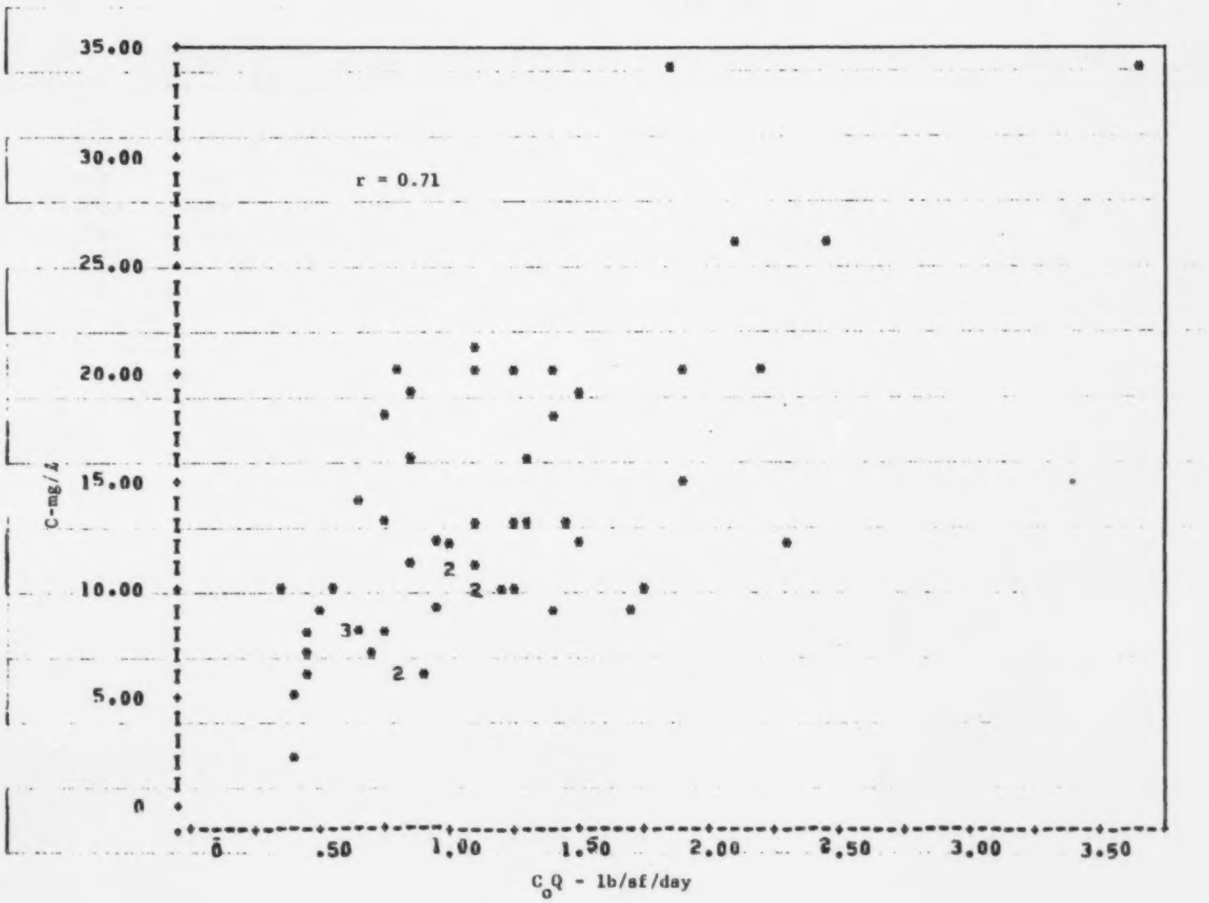


Figure 29. C vs. solids loading, Marionbrook - Jan.-Feb. 1976.

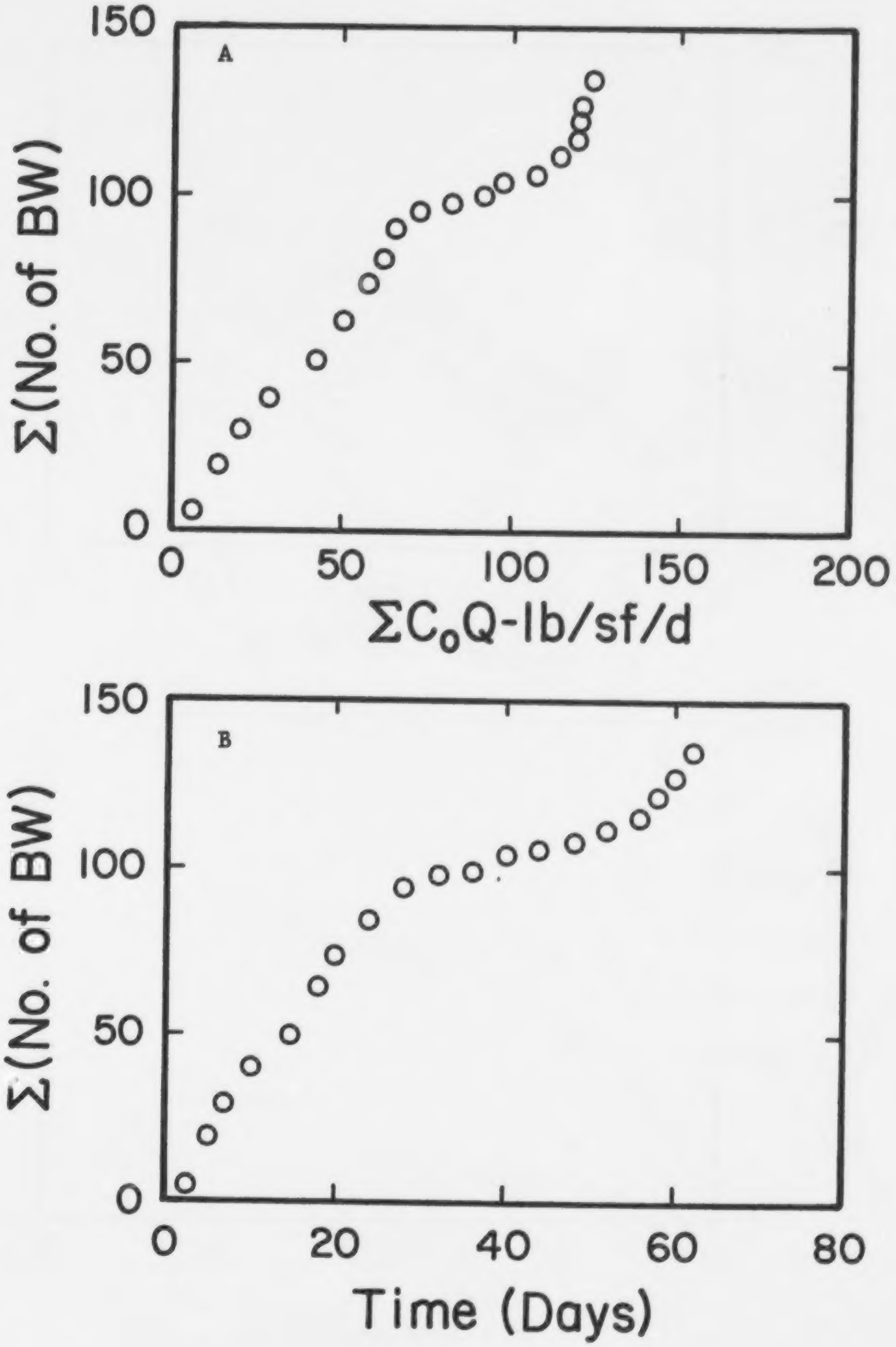


Figure 30. Cumulative backwashes by headloss vs. solids loading and time, Addison North - Phase 1.

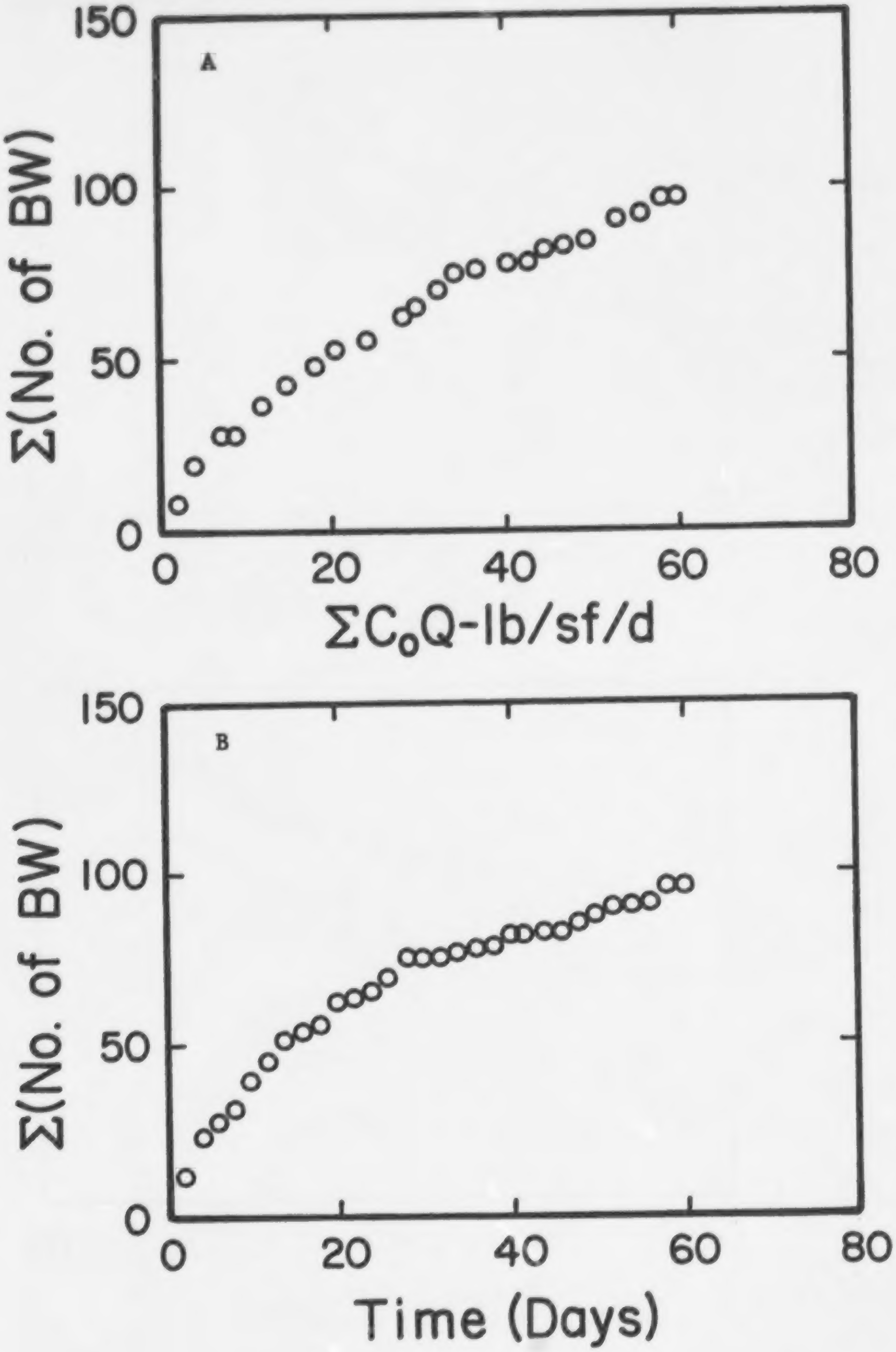


**Figure 31.** Cumulative backwashes by headloss vs. solids loading and time, Addison South - Phase 1.

Table 17. Addison North and South Plants - Mean performance data and bivariate correlation coefficients for segmenting data, Phase I.

| | All Data | May 20- July 1 | July 2- Aug. 7 |
|---|---|---|---|
| | ADDISON NORTH | | |
| No. of cases | 73 | 37 | 36 |
| Q-gpm/sf | 3.8 | 4.2 | 3.3 |
| No. of BW | 3.3 | 4.5 | 2.1 |
| $C_o$ - mg/ℓ | 44 | 50 | 39 |
| C - mg/ℓ | 6.5 | 6.5 | 6.6 |
| $C/C_o$ | .173 | .121 | .174 |
| $C/C_o$ to: | | | |
| Q | -.07 | .20 | -.01 |
| Qt | .05 | .16 | -.24 |
| t | .04 | .07 | -.26 |
| C to: | | | |
| $C_o$ | .26 | .21 | .32 |
| Q | .06 | .10 | .09 |
| $C_oQ$ | .29 | .30 | .33 |
| t | -.05 | -.07 | -.05 |
| | ADDISON SOUTH | | |
| No. of cases | 70 | 34 | 36 |
| Q-gpm/sf | 2.1 | 2.3 | 1.9 |
| No. of BW | 2.8 | 4.1 | 1.7 |
| $C_o$ - mg/ℓ | 37 | 42 | 32 |
| C - mg/ℓ | 9.0 | 9.4 | 8.7 |
| $C/C_o$ | .262 | .220 | .259 |
| $C/C_o$ to: | | | |
| Q | 0 | .14 | -.04 |
| Qt | .19 | .16 | .16 |
| t | .18 | .12 | .13 |
| C to: | | | |
| $C_o$ | .40 | .38 | .42 |
| Q | .02 | -.11 | .21 |
| $C_oQ$ | .23 | .12 | .39 |
| t | -.27 | -.34 | -.11 |

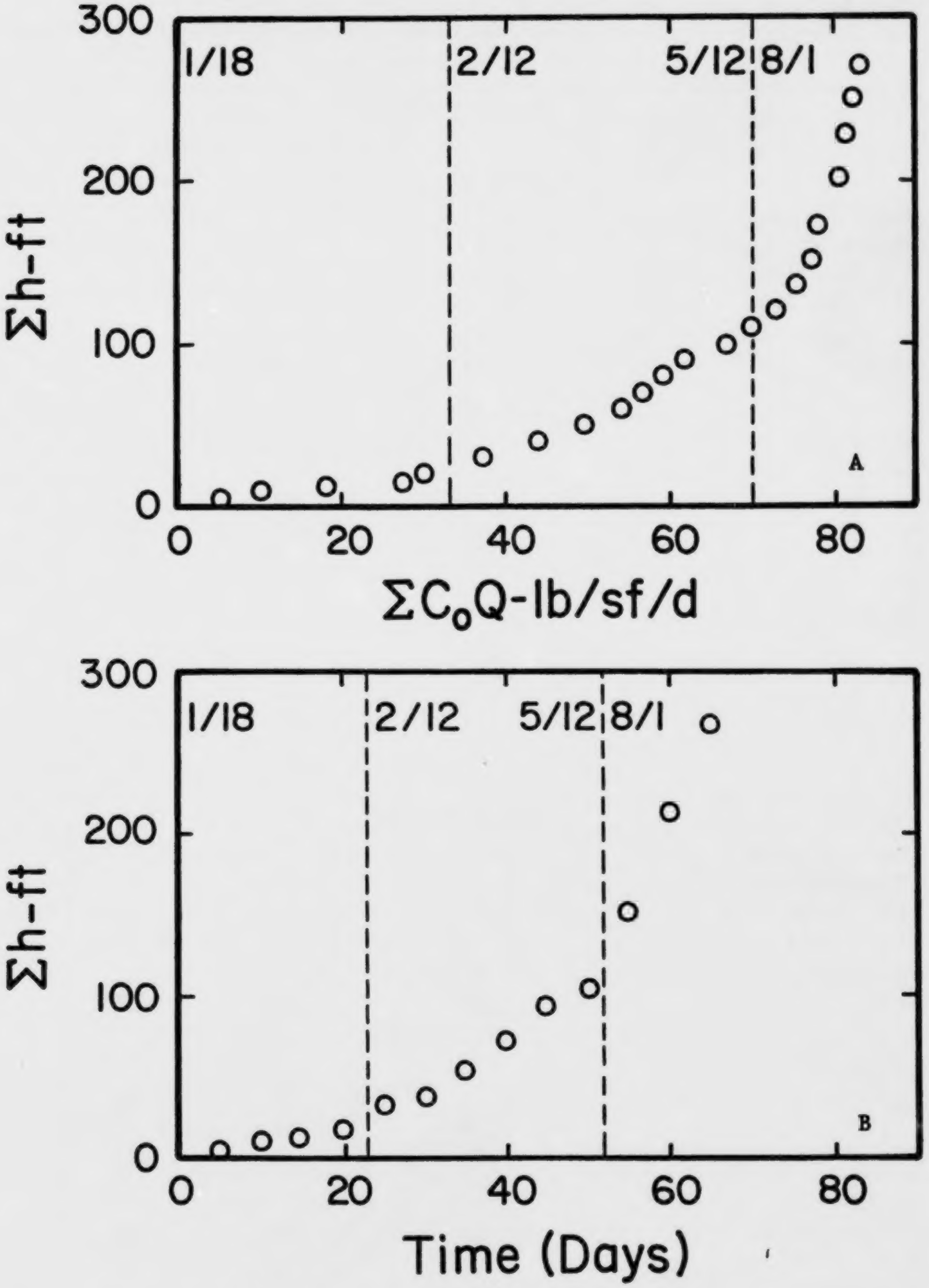


Figure 32. Cumulative headloss vs. solids loading and time, Marionbrook, Medium flow - Phase 1.

depth filtration was considered to be the dominant particle collection mode. On February 11, 1976, heavy rains along with melting snow occurred, headloss buildup was very rapid, and straining was considered to dominate. Greatly improved correlations were obtained for segmenting the dry weather data on this basis (Figure 29). Filters backwashed frequently during a second testing period in August, 1976. These backwash data are suspect because of malfunctions in control systems.

### Grouping by Ranges of Filter Influent Suspended Solids

Data for each plant were grouped into three $C_o$ ranges; less than 35 mg/ℓ, 35-50 mg/ℓ, and greater than 50 mg/ℓ. No significant improvements in correlation of the data were obtained by this approach.

### Ratio of Solids Capture to Headloss Increase

The ratio of solids capture to headloss increase, measured as weight of suspended solids captured per unit of total bed headloss buildup, excluding the clean-bed headloss, is a measure of the amount of material that can be stored in a filter bed during a run (Dahab and Young, 1977). This ratio should also be indicative of the type of particle collection mode since a large solids capture ratio should be characteristic of in-depth filtration.

Data for the Addison South plant were segmented for the solids capture ratio ($S_{ch}$) less than or equal to and greater than 0.1 lb/ft$^2$. This value was selected to segment the data into two approximately equal groups. Regression coefficients for a model of the form $C = C_o^b Q^c$, where a, b, and c are constants, are shown in Table 18 along with mean performance data. Multiple correlation coefficients for the logarithmic transformed equation for segmenting the data are nearly identical. The data, except for similar performance at the medium flow rate, indicate higher removal efficiency for the high $S_{ch}$ range. This suggests that removal efficiency may be higher for in-depth as compared to straining filtration. This concept is explored further in the next section.

## HEADLOSS AND SOLIDS CAPTURE RATIOS

Headloss and solids capture data are shown in Table 19 for the Addison South, Lake Zurich, and Marionbrook plants for runs where an intermediate backwash did not occur. The accuracy of the data is poor at high solids capture ratios because headlosses are less than 0.1 ft. Mean solids capture varied from 0.15 to over 2 lb/ft$^2$/ft.

Although correlation coefficients are generally low, the Addison South and Lake Zurich data show a decrease in $C/C_o$ with increasing solids capture ratios. This is also shown in Table 18 for Addison South. No explanation can be given why there is no apparent trend for the Marionbrook data. The highest bivariate correlation coefficients occur for C and $C/C_o$ to headloss for low flow for Addison South and Lake Zurich. At lower flows, there is less penetration of particles into the bed as compared to high flows. The decrease in clarification efficiency may possibly be caused by deeper floc penetration at high headloss. Plots of C vs. headloss and solids capture ratio are shown in

Table 18. Addison South Plant - separation of data sets for low and high solids capture ratios - Phase 1.

Regression Coefficients for $C = aC_o^bQ^c$

| | No. of Cases | $r_t$ | a | b | c |
|---|---|---|---|---|---|
| **Phase 1** | | | | | |
| All Data | 176 | .58 | 1.13 | .57 | .41 |
| Sch ≦ 0.1 | 73 | .63 | .88 | .69 | .29 |
| Sch > 0.1 | 103 | .60 | 1.29 | .49 | .52 |

Mean Performance Data

| | All | Low Q | Med Q | High Q |
|---|---|---|---|---|
| All Phase 1 No.of cases | 176 | 61 | 51 | 64 |
| Q-gpm/sf | 2.06 | 0.87 | 1.76 | 3.43 |
| C-mg/ℓ | 15.3 | 11.2 | 13.7 | 20.5 |
| $C_o$-mg/ℓ | 50.9 | 52.3 | 48.9 | 51.3 |
| $C/C_o$ | .314 | .235 | .300 | .401 |
| Sch ≤ 0.1 No. of cases | 73 | 28 | 17 | 28 |
| Q-gpm/sf | 2.08 | 0.87 | 1.67 | 3.53 |
| $C_o$-mg/ℓ | 17.3 | 14.3 | 13.4 | 22.7 |
| $C_o$-mg/ℓ | 50.5 | 50.8 | 49.3 | 50.8 |
| $C/C_o$ | .362 | .310 | .299 | .451 |
| Sch > 0.1 No.of cases | 103 | 33 | 34 | 36 |
| Q -gpm/sf | 2.05 | .86 | 1.81 | 3.36 |
| C-mg/ℓ | 13.9 | 8.6 | 13.9 | 18.7 |
| $C_o$-mg/ℓ | 51.3 | 53.5 | 48.7 | 51.7 |
| $C/C_o$ | .283 | .176 | .301 | .365 |

Table 19. Headloss and solids capture data - Phase 1.

| Plant | No. of Cases | h-ft. | | Sc-lb/ft$^2$ | | Sch-(lb/ft$^2$)/ft | | r - C to: | | r-C/$C_o$ to: | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean | Range | Mean | Range | Mean | Range | h | Sch | h | Sch |
| **Addison South** | | | | | | | | | | | |
| **Low Q** | 37 | 1.6 | 0.1-3.2 | .33 | .06-1.6 | 1.0 | .02-9.1 | .61 | -.45 | .52 | -.46 |
| **Med. Q** | 36 | 2.6 | .03-5.5 | .44 | .06-2.2 | .19 | .02-.9 | -.06 | .15 | -.29 | -.22 |
| **High Q** | 49 | 4.6 | .7-12 | .84 | .3-5.2 | .22 | .06-1.2 | .46 | -.13 | .07 | -.32 |
| **Lake Zurich** | | | | | | | | | | | |
| **Low Q** | 13 | 0.9 | .1-3.4 | .18 | .06-.3 | .62 | .02-2.3 | .76 | -.82 | .56 | -.84 |
| **Med. Q** | 18 | 0.9 | .1-2.7 | .20 | .07-.5 | .36 | .08-.7 | .55 | -.23 | .44 | -.16 |
| **Marionbrook**<br>**Dry Weather-Jan-Feb'76** | | | | | | | | | | | |
| **Low Q** | 21 | 0.8 | .2-2.9 | .33 | .09-1.0 | .55 | .05-2.0 | .08 | .38 | .14 | -.10 |
| **Med. Q** | 26 | 0.7 | .1-3.4 | .48 | .08-1.5 | 2.3 | .1-15 | -.29 | .47 | -.26 | -.06 |
| **1st Half Wet Weather** | | | | | | | | | | | |
| **Low Q** | 30 | 1.6 | .1-5.0 | .21 | .03-.62 | .33 | .01-1.9 | .12 | -.17 | -.25 | 0 |
| **Med. Q** | 21 | 1.5 | .2-3.8 | .19 | .02-.43 | .31 | .02-1.4 | .37 | -.08 | -.03 | -.11 |
| **High Q** | 20 | 1.9 | .2-4.2 | .38 | .04-1.6 | .42 | .02-1.8 | .19 | -.08 | .23 | -.06 |
| **2nd Half Wet Weather** | | | | | | | | | | | |
| **Low Q** | 32 | 2.0 | .2-5.3 | .22 | .02-1.2 | .15 | .01-.89 | -.03 | .16 | -.09 | -.19 |
| **Med. Q** | 27 | 2.1 | .2-4.9 | .29 | .07-.43 | .25 | .03-2.6 | .13 | .04 | .17 | -.18 |

Figure 33 for the Lake Zurich plant. The Lake Zurich filters were not always backwashed at the start of runs in order to obtain data on the effect of run length on filter performance. Figure 33 shows that C generally increased with higher headloss and decreased with higher solids capture ratios, although the high solids capture ratios (0.1 ft. headloss) tend to distort the plots. A similar result is shown in Figure 34 for plots of $C/C_o$ vs. headloss and solids capture ratio.

## DEVELOPMENT AND TESTING OF OPERATIONAL MATHEMATICAL MODELS--PHASE 1 DATA

Data from this phase were analyzed using the three models shown in Equations 18, 19, and 20, using multiple regressions and log transformations. Selected models were then compared with data from other plants.

### Regression Coefficients for Models

A convenient method for analyzing the effect of a number of independent variables on a dependent variable is to conduct a series of multiple regression analyses and add a new variable each time. The regression coefficients in the assumed power law relations can then be compared with results expected from theory.

Regression coefficients for the three models using all Phase 1 data are given in Table 20. For the Model I, the regression coefficient for viscosity has the wrong sign since, from theory, it would be expected that C would increase at higher viscosity. The significance level, or probability that the result occurred by chance, for equivalent media diameter is high. The coefficient for $d_e$, however, has the correct sign. From Figure 21. the values for $d_e$ do not vary widely except for the large diameter media at the Addison plants. This result may be caused in part by the high removal efficiency for the Addison North plant. Correlation coefficients are not improved significantly by the use of variables other than $C_o$ and Q.

For Models II and III, the coefficient for viscosity also has the wrong sign. For the Model II inclusion of L and $d_e$ does not improve correlations. The regression coefficients for Q of about -0.25 are in the lower range of those reported in the literature. For Model III, a very poor correlation is obtained when only $C_o$ and Q are included. This suggests that the filter clarification efficiency is relatively independent of depth for these filters, as shown from analysis of the average plant data.

Regression coefficients for the four variable flow plants, excluding the wet weather flow data for Marionbrook, are shown in Table 21. The model for C yielded a positive exponent for L and a negative exponent for $d_e$, neither of which would be expected from theory. However, only four different media specifications, with ranges of $d_e$ of 0.8 to 1.7 mm. and L of 12 to 45 in., were included in the analysis.

It is clear that the inclusion of independent variables other than $C_o$ and Q in models cannot be justified without inclusion of other variables discussed in Chapter X. The model of choice without such variables then becomes

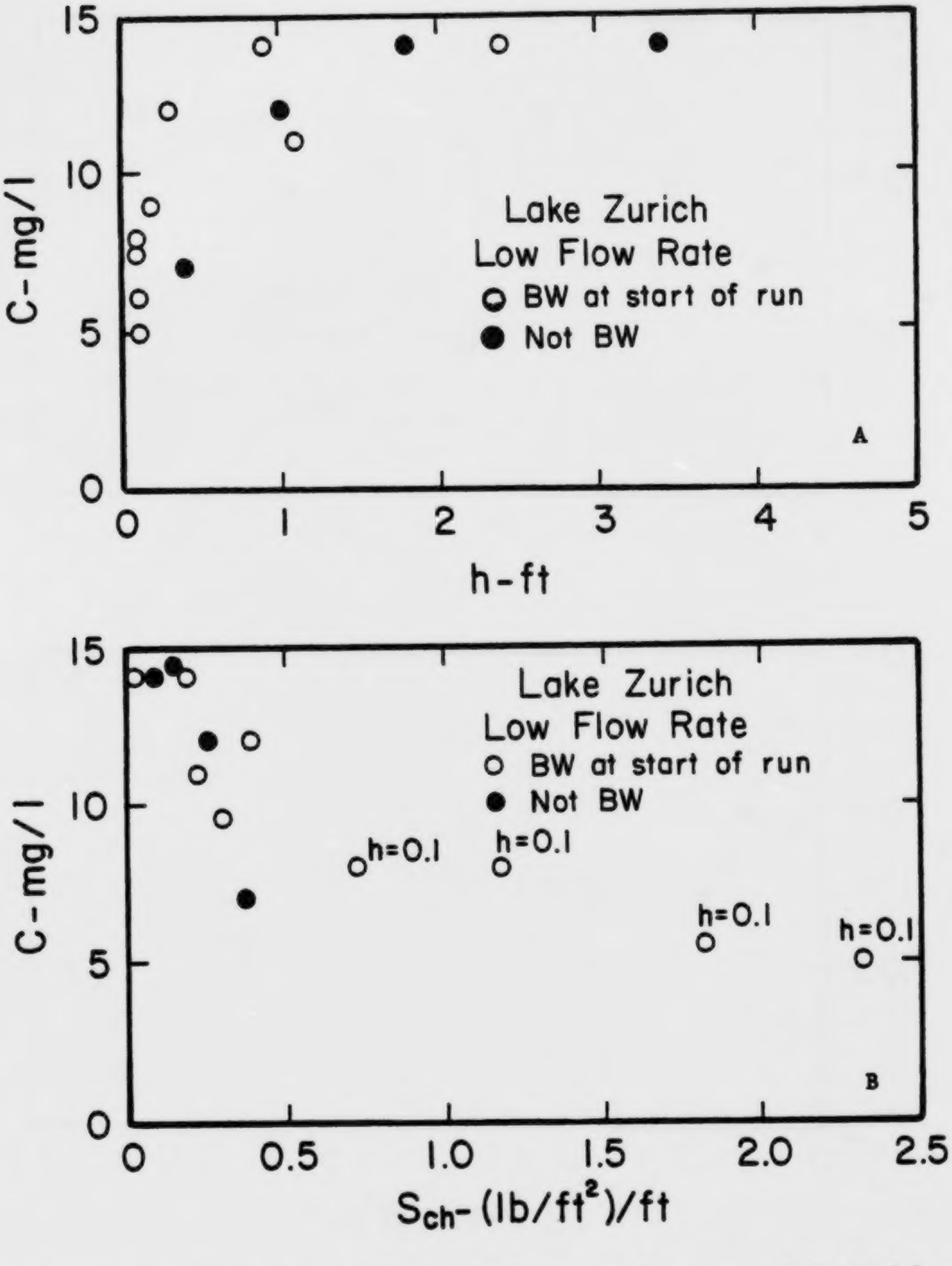


Figure 33. C vs. headloss and solids capture/headloss, Lake Zurich - Phase 1.

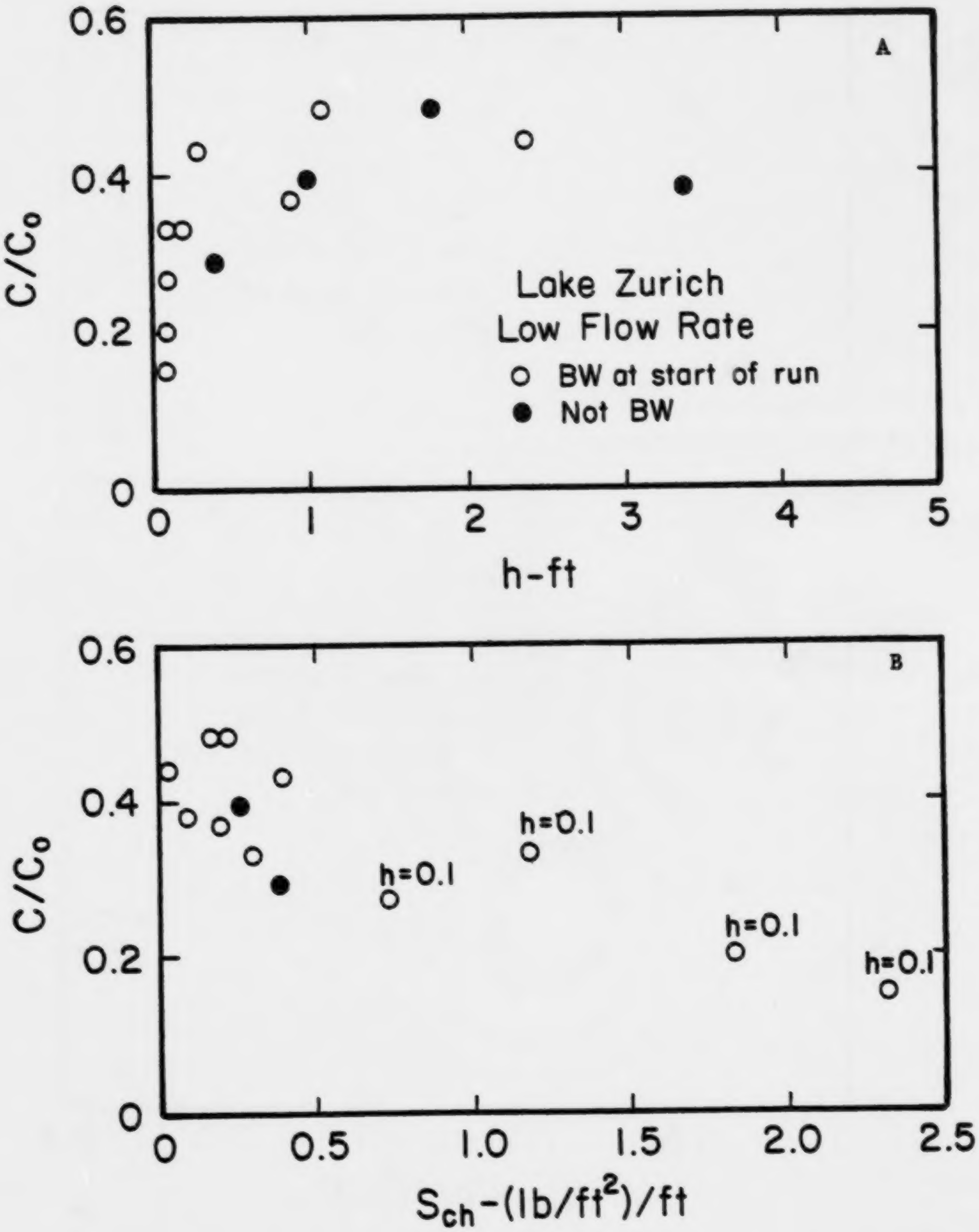


Figure 34. $C/C_o$ vs. headloss and solids capture/headloss, Lake Zurich - Phase 1.

Table 20. Regression coefficients - all Phase 1 data.

| Model | Variables Included | $r_t$ | Regression Coefficients | | | | |
|---|---|---|---|---|---|---|---|
| | | | b | c | d | e | f |
| I | $C = a\ C_o^b Q^c \mu^d L^e d_e^f$ | | | | | | |
| | $C_o$,Q | .42 | .56 | .36 | - | - | - |
| | $C_o$,Q,$\mu$ | .44 | .53 | .34 | -.98 | - | - |
| | $C_o$,Q,$\mu$,L | .45 | .56 | .34 | -1.32 | -.16 | - |
| | $C_o$,Q,$\mu$,L,$d_e$ | .46 | .54 | .36 | -1.07 | -.30 | .36 |
| | (Significance) | | (0) | (0) | (0) | (0) | (0) |
| II | $\text{Log}\ \frac{C}{C_o} = aC_o^b Q^c \mu^d L^e d_e^f$ | | | | | | |
| | $C_o$,Q | .43 | .34 | -.26 | - | - | - |
| | $C_o$,Q,$\mu$ | .45 | .36 | -.25 | .75 | - | - |
| | $C_o$,Q,$\mu$,L | .46 | .34 | -.25 | 1.03 | .14 | - |
| | $C_o$,Q,$\mu$,L,$d_e$ | .47 | .35 | -.26 | .85 | .24 | -.26 |
| | (Significance | | (0) | (0) | (0) | (0) | (0) |
| | Q,$\mu$,L,$d_e$ | .34 | - | -.23 | .74 | .27 | -.17 |
| | (Significance) | | (0) | (0) | (0) | (.01) | (.07) |
| III | $\frac{1}{L}\ \text{Log}\ \frac{C}{C_o} = aC_o^b Q^c \mu^d d_e^f$ | | | | | | |
| | $C_o$,Q | .25 | .11 | -.27 | - | - | - |
| | $C_o$,Q,$\mu$ | .45 | .19 | -.22 | 2.87 | - | - |
| | $C_o$,Q,$\mu$,$d_e$ | .61 | .31 | -.27 | 1.37 | - | -1.01 |
| | (Significance) | | (0) | (0) | (0) | | (0) |
| | Q,$\mu$,$d_e$ | .57 | - | -.24 | 1.26 | - | -.90 |
| | (Significance) | | | | | | |

Table 21. Regression coefficients, variable flow plants - Phase 1.

| Model | Variables Included | $r_t$ | Regression Coefficients | | | | |
|---|---|---|---|---|---|---|---|
| | | | b | c | d | e | f |
| IV | $C = aC_o^{b}Q^{c}\mu^{d}L^{e}d_e^{f}$ | | | | | | |
| | $C_o, Q$ | .54 | .46 | .33 | - | - | - |
| | $C_o, Q, \mu$ | .55 | .47 | .33 | .32 | - | - |
| | $C_o, Q, \mu, L$ | .55 | .46 | .35 | .44 | .084 | - |
| | $C_o, Q, \mu, L, d_Q$ | .56 | .43 | .36 | .67 | -.29 | -.62 |
| | (Significance) | | (0) | (0) | (.06) | (.03) | (0) |
| V | $\text{Log}\ \frac{C}{C_o} = aC_o^{b}Q^{c}\mu^{d}L^{e}d_e^{f}$ | | | | | | |
| | $C_o, Q$ | .53 | .45 | -.28 | - | - | - |
| | $C_o, Q, \mu$ | .53 | .46 | -.28 | .061 | - | - |
| | $C_o, Q, \mu, L$ | .53 | .46 | -.29 | .021 | .028 | - |
| | $C_o, Q, \mu, L, d_Q$ | .55 | .49 | -.31 | -.20 | .34 | -.61 |
| | (Significance) | | (0) | (0) | (.51) | (0) | (0) |
| | $Q, \mu, L, d_Q$ | .34 | - | -.27 | -.53 | .27 | -.33 |
| | (Significance) | | | (0) | (.12) | (.04) | (.09) |
| VI | $\frac{1}{L}\ \text{Log}\ \frac{C}{C_o} = aC_o^{b}Q^{c}\mu^{d}d_e^{f}$ | | | | | | |
| | $C_o, Q$ | .17 | .22 | -.019 | - | - | - |
| | $C_o, Q, \mu$ | .25 | .27 | -.028 | 1.51 | - | - |
| | $C_o, Q, \mu, d_Q$ | .72 | .50 | -.29 | -.33 | - | -1.48 |
| | (Significance) | | (0) | (0) | (.31) | | (0) |
| | $Q, \mu, d_Q$ | .62 | - | -.26 | -.67 | - | -1.29 |
| | (Significance) | | | (0) | (.06) | | (0) |

$$C = a\ C_o^b\ Q^c \qquad (21)$$

where a, b, and c are constants.

## Models for Individual Plant Data

Regression coefficients were generated from data sets for the model $C = a\ C_o^b\ Q^c$ and are shown in Table 22 with the multiple correlation coefficients ($r_t$) for the assumed relationship. For plants where flow was not varied to individual filters, the coefficient c on superficial flow had a negative value for two plants; negative values are not expected since filter performance should deteriorate at higher flow rates. For variable flow plants, the coefficient c ranged from 0.32 to 0.5 for most data and multiple correlation coefficients varied from 0.26 to 0.72. The coefficient for $C_o$ varied from about 0.2 to 0.9.

Data for the Marionbrook plant were obtained during the period from January to August, 1976. Data were analyzed separately for both dry and wet weather periods. Prior to melting snow and heavy rains in mid-February, headloss buildup was less than 2 ft/day and in-depth filtration was believed to be the dominant particle collection mode. For this period, the bivariate correlation coefficient between C and $C_oQ$ was 0.71. From Table 22, the highest multiple correlation coefficient of 0.77 was obtained for an equation of the form:

$$C = 0.40\ C_o^{.86} Q^{.34} \qquad (22)$$

During the wet weather flow periods at the Marionbrook plant, flow generally was higher by a factor of two, headloss buildup was very rapid, and straining or semi-cake filtration was considered to dominate.

Scattergrams of calculated vs. measured C are shown in Figures 35, 36, 37A and 37B for the Addison South, Lisle, Lake Zurich, and Marionbrook (dry weather) models, respectively. If a model provides an accurate description of the filtration process, although some scatter of the data would be present, it would be expected that a line of best fit would have an intercept close to zero and a slope close to 1. The intercepts and slopes for the scattergrams are given in Table 23. In each case, a positive intercept at zero measured C and a slope considerably less than 1 are present. Thus the models tend to overpredict C at lower values of measured C and underpredict at higher values. The Marionbrook model provides the best fit with an r of 0.84, an intercept of 4.4 mg/ℓ, and a slope of 0.57.

## Testing of Models

Each of the models developed from variable-flow plant data was tested using other data sets, and scattergrams of calculated vs. measured C were prepared. Correlation coefficients, intercepts, and slope are given in Table 23. Typical scattergrams are shown in the following figures.

Table 22. Regression coefficients for $C = aC_o^bQ^c$ - Phase 1 data.

| Plant<br>Non-Variable Flow | Mult $r_t$ | a | b | c |
|---|---|---|---|---|
| Addison North | .26 | 1.49 | .28 | .25 |
| Addison South | .34 | 2.34 | .38 | -.11 |
| Barrington | .67 | .70 | .87 | -.29 |
| Des Plaines River | .39 | 2.37 | .24 | .50 |
| Romeoville | .57 | .65 | .64 | .55 |
| Variable Flow | | | | |
| Addison South | .58 | 1.13 | .57 | .41 |
| Lake Zurich | .65 | 1.73 | .49 | .41 |
| Lisle | .56 | 1.46 | .38 | .50 |
| Marionbrook | | | | |
| Dry weather | .77 | .40 | .86 | .34 |
| 1st half wet weather | .44 | 1.52 | .35 | .32 |
| 2nd half wet weather | .37 | .62 | .44 | .16 |

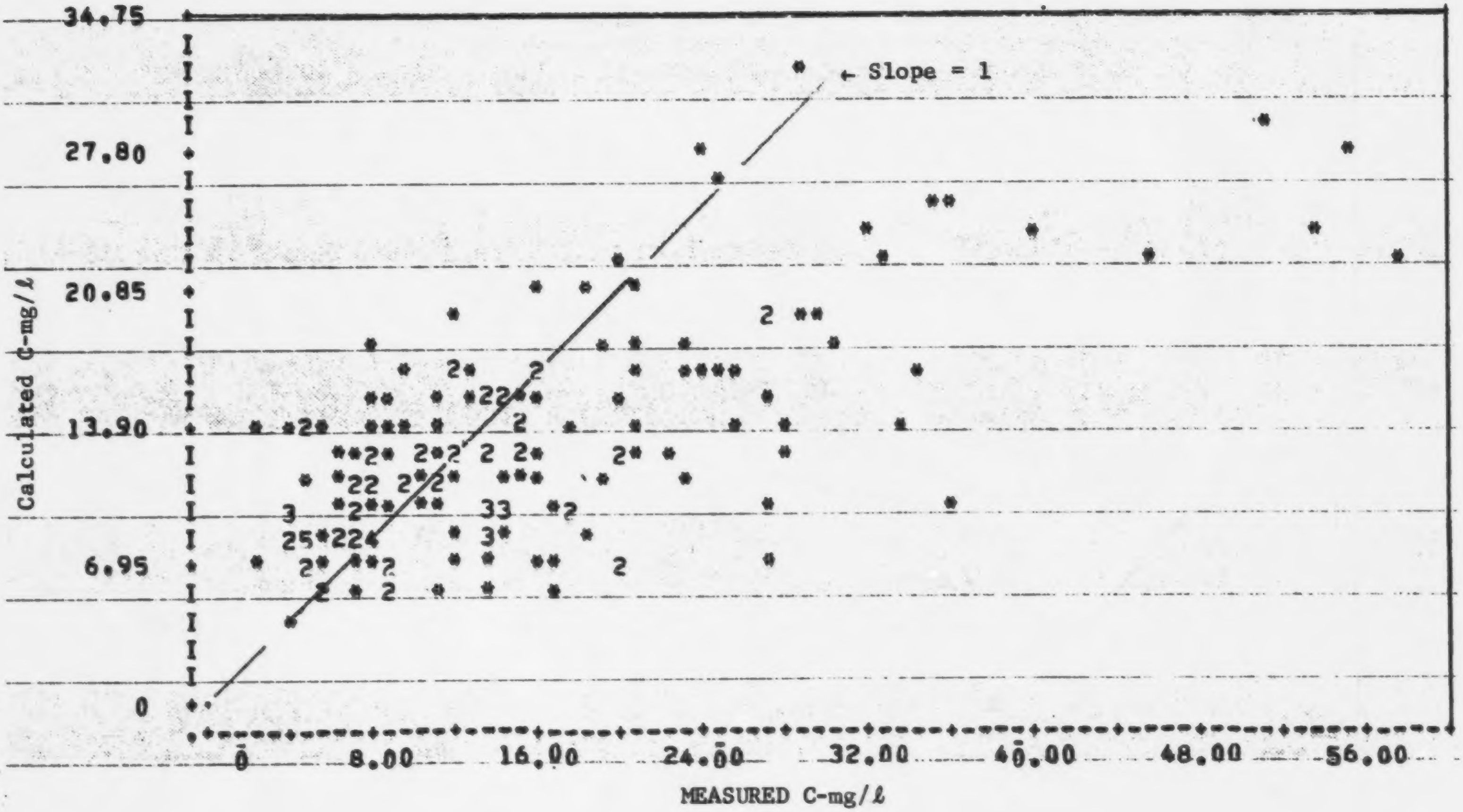


Figure 35. Calculated vs. measured C, Addison South Model, Addison South data.

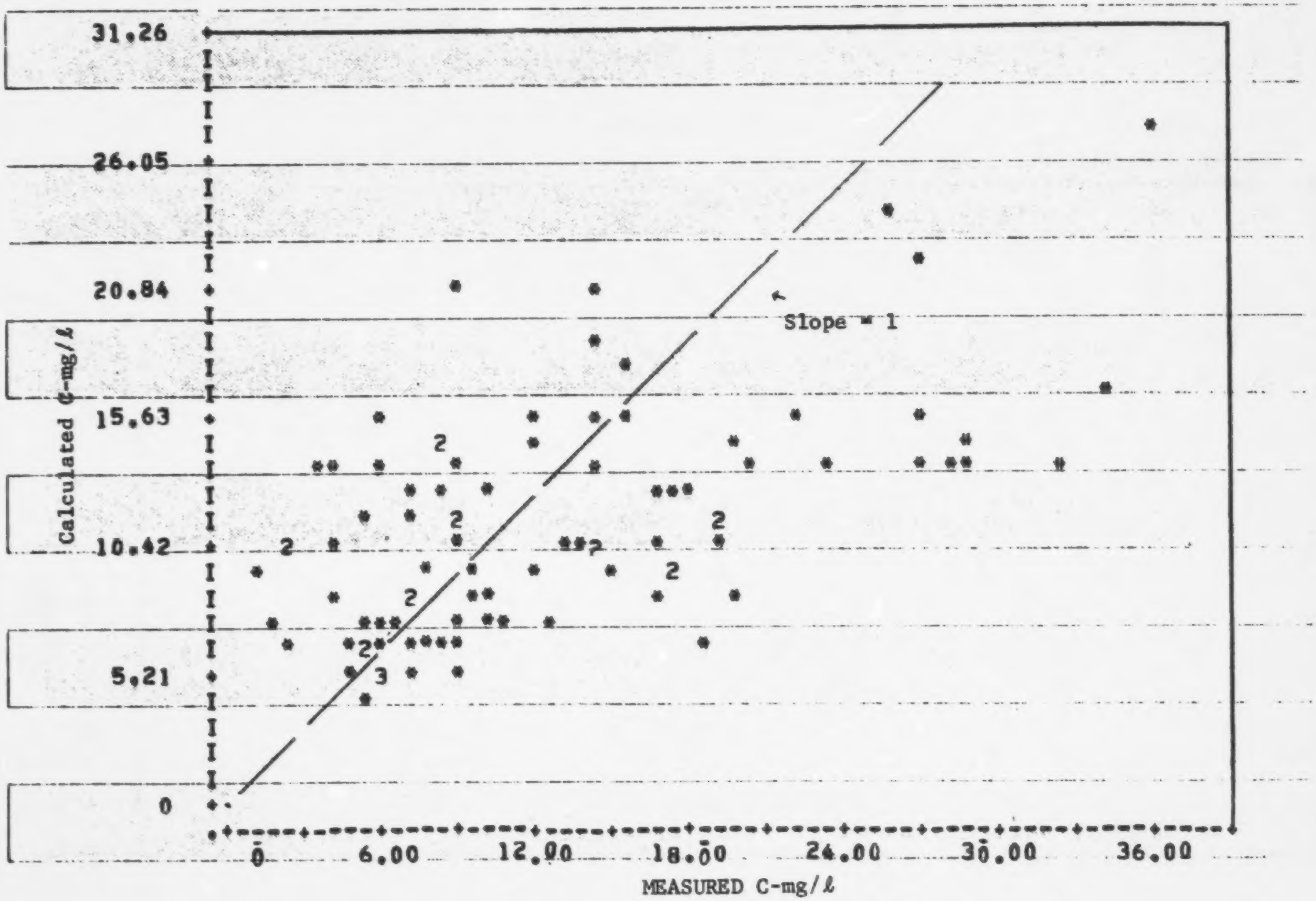
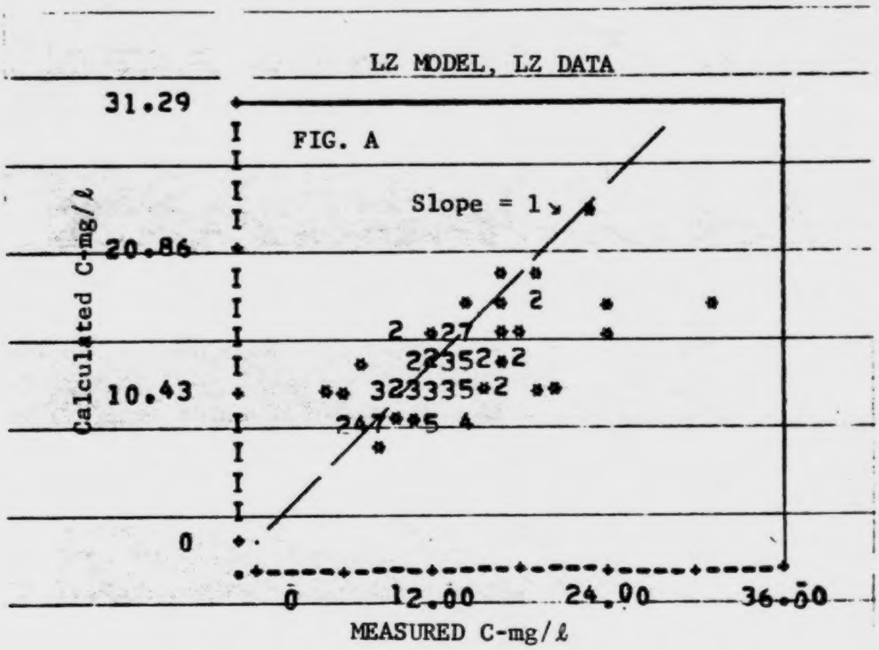


Figure 36. Calculated vs. measured C, Lisle Model, Lisle data.



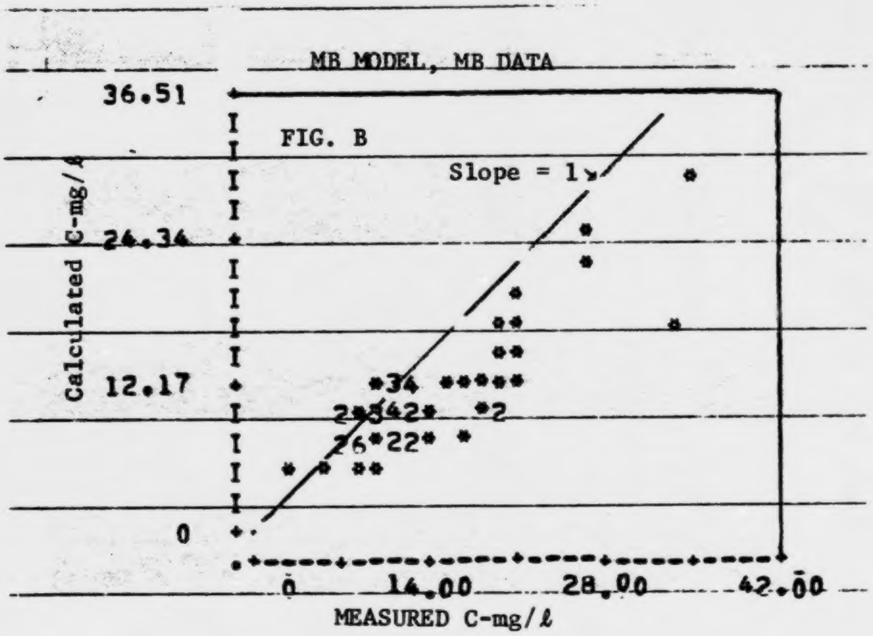


Figure 37. Calculated vs. measured C, Lake Zurich and Marionbrook.

Table 23. Testing of regression equations of form $C = aC_o^bQ^c$ - Phase 1.

| Model | Addison South | | | Lake Zurich | | | Lisle | | | Marionbrook-Dry Weather | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $r_t$ for eq | | .58 | | | .65 | | | .56 | | | .77 | |
| Regression Coefficients | | | | | | | | | | | | |
| a | | 1.13 | | | 1.73 | | | 1.46 | | | .40 | |
| b | | .57 | | | .49 | | | .38 | | | .86 | |
| c | | .41 | | | .41 | | | .50 | | | .34 | |
| Data Set | r | int. | sl. | r | int. | sl. | r | int. | sl. | r | int. | sl. |
| Non-Variable Flow | | | | | | | | | | | | |
| AN | .27 | 14 | .32 | .27 | 16 | .32 | .26 | 10 | .17 | .26 | 13 | .44 |
| AS | .35 | 9.2 | .30 | .34 | 11 | .30 | .31 | 7.0 | .14 | .36 | 7.7 | .44 |
| BA | .50 | 9.5 | .47 | .49 | 12 | .46 | .45 | 7.9 | .25 | .53 | 7.0 | .59 |
| DP | .44 | 4.6 | .44 | .44 | 5.6 | .45 | .44 | 3.3 | .23 | .43 | 3.9 | .60 |
| RO | .68 | 5.4 | .46 | .67 | 6.9 | .46 | .62 | 4.6 | .21 | .68 | 3.2 | .70 |
| Variable Flow | | | | | | | | | | | | |
| AV | .67 | 8.3 | .34 | .67 | 9.7 | .35 | .65 | 5.6 | .21 | .66 | 7.9 | .43 |
| LZ | .65 | 5.6 | .41 | .65 | 7.0 | .43 | .62 | 4.5 | .26 | .64 | 3.8 | .46 |
| LI | .55 | 12 | .43 | .57 | 14 | .44 | .59 | 8.3 | .27 | .48 | 12 | .55 |
| MB Dry Weather | .75 | 7.0 | .42 | .73 | 9.0 | .41 | .61 | 6.4 | .20 | .84 | 4.4 | .57 |
| 1st Half Wet | .42 | 8.4 | .44 | .42 | 9.9 | .47 | .40 | 6.0 | .30 | .39 | 7.6 | .47 |
| 2nd Half Wet | .48 | 7.0 | .76 | .47 | 8.4 | .78 | .45 | 5.2 | .45 | .46 | 6.0 | .93 |

| Figure | Model | Data Set |
|---|---|---|
| 38 | Addison South | Marionbrook (dry weather) |
| 39 | Lake Zurich | Addison South (var. flow) |
| 40 | Lisle | Lake Zurich |
| 41 | Marionbrook | Lisle |

In every case, positive intercepts and slopes less than one were obtained.

Plots of calculated vs. measured C using the Marionbrook Model (dry weather flow) are shown in Figure 42 for Hsiung's data (1972) and in Figure 43 for other published data. A poor fit of the model is apparent for Hsiung's data. In Figure 43 , the data reported by EPA (1975) provide the best fit. Most of the EPA (1975) data are from full scale sand filters in Great Britain.

## DISCUSSION

Performance of tertiary filters is the result of complex interactions between a number of variables. Changes in the characteristics of secondary effluent suspended solids, believed to be a major variable, can occur on a seasonal or daily basis, or over a shorter time frame during filter runs. Causes include changes in secondary process biota, changes in process operating modes, process upsets, and flow surges causing temporary loss of floc from secondary sedimentation tanks. Parameters of importance that were not measured routinely in this phase include particle size characteristics, floc strength, and particle surface charge properties. Even so, it was found that if filtration process data are analyzed over shorter time frames where suspended solids character is more constant, improved correlations can be obtained with simple correlations.

In pilot-scale studies on filtration of activated sludge process effluents, Tchobanoglous (1970) reported that media grain size had a significant effect on removal efficiency for single medium sand and anthracite filters at depths from 18 to 30 in. Influent suspended solids levels for his studies varied from approximately 14 to 24 mg/ℓ. Small removals of suspended solids occurred below depths of 16 to 20 in. Baumann and Huang (1974) reported that variations in performance over a wide range of media sizes were not significant for dual media pilot-scale filtration of trickling filter process effluents. Trickling filter effluent suspended solids varied from 15 to 50 mg/ℓ. It was reported that no significant removal occurred below depths of 12 in. for both the sand and anthracite media. In pilot-scale studies using unstratified bed filters, Dahab and Young (1977) concluded that removal efficiency is not reduced greatly by increasing the effective size ($d_{10}$) of media from 1 to 2 mm at flow rates of 2 to 4 gpm/sf. Influent suspended solids levels for their studies ranged from approximately 20 to 50 mg/ℓ.

In the studies reported by Tchobanoglous (1970), influent solids levels were much lower than the averages of 28 to 62 mg/ℓ observed for the plants in this full-scale investigation. At lower solids levels, it would be expected that mean particle size would be smaller and media grain size would have a greater influence on removal efficiency than in this study.

Media grain size and depth did not have an apparent significant effect on filter clarification efficiency for the full-scale plants in this study. Al-

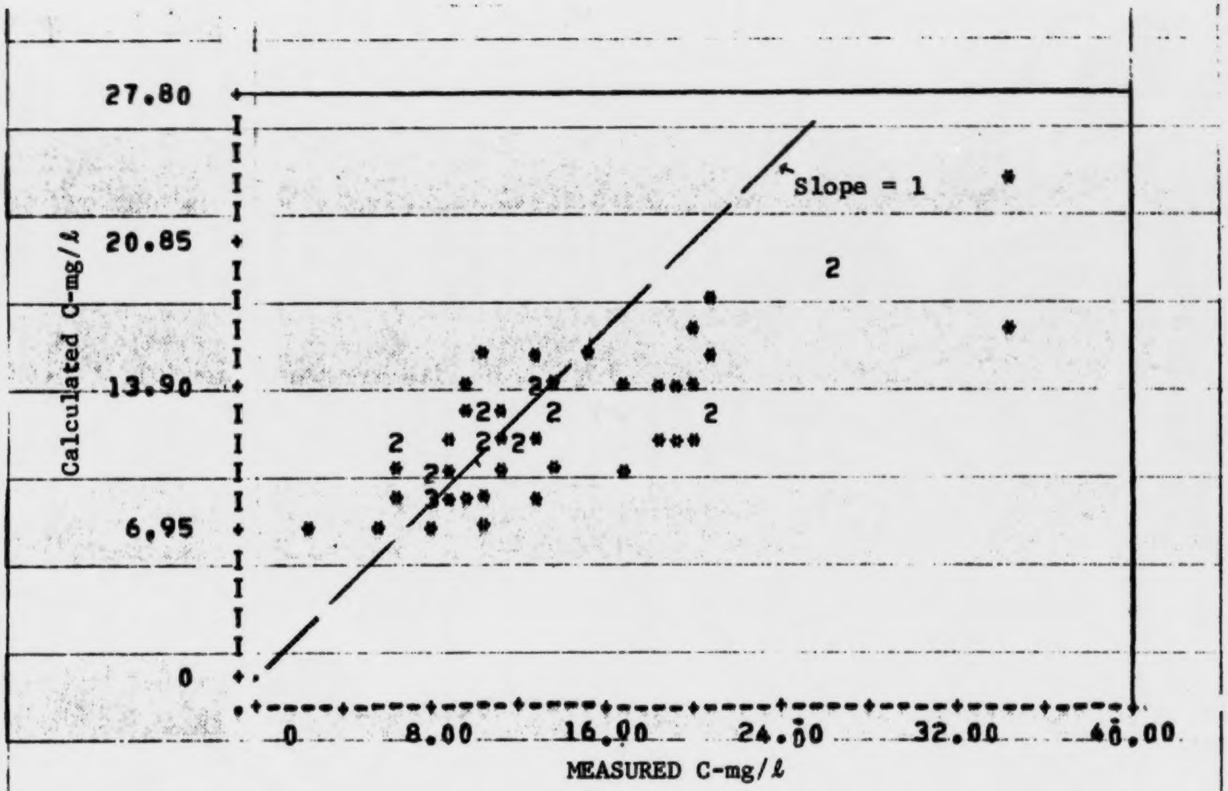


Figure 38. Calculated vs. measured C, Addison South Model, Marionbrook data.

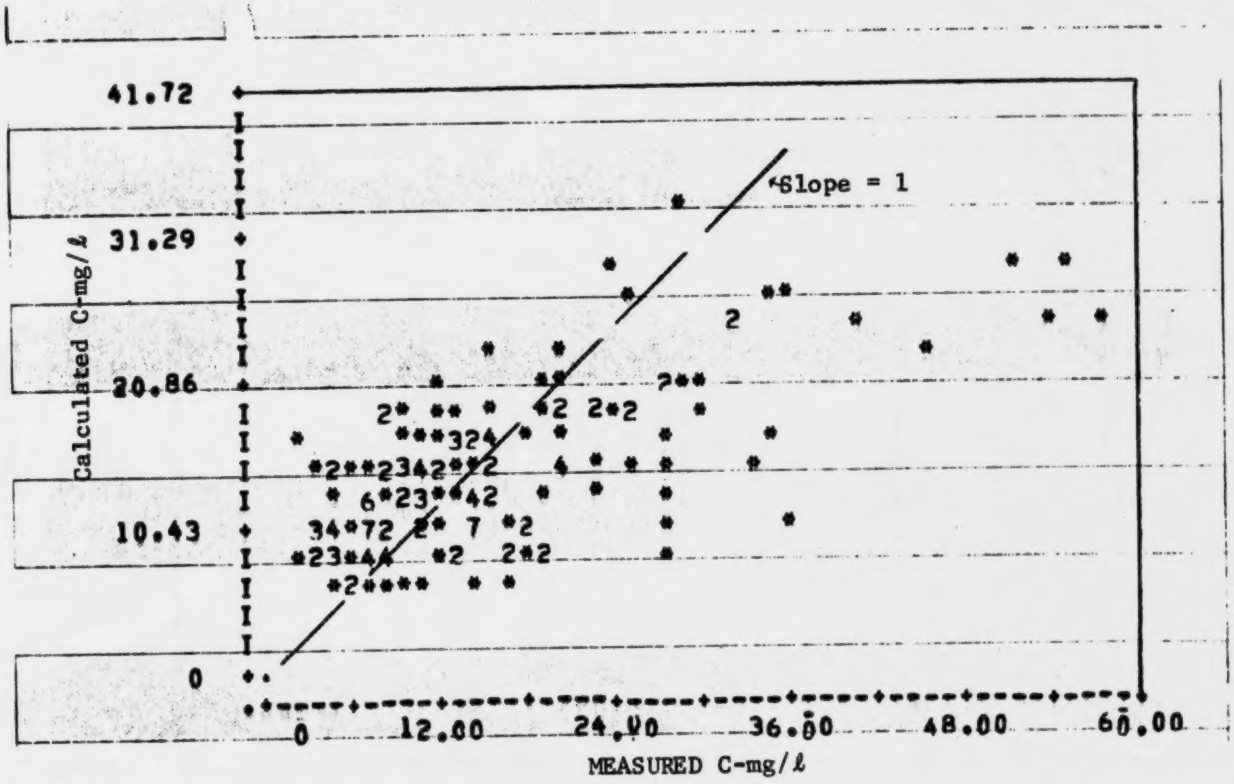


Figure 39. Calculated vs. measured C, Lake Zurich model, Addison South data.

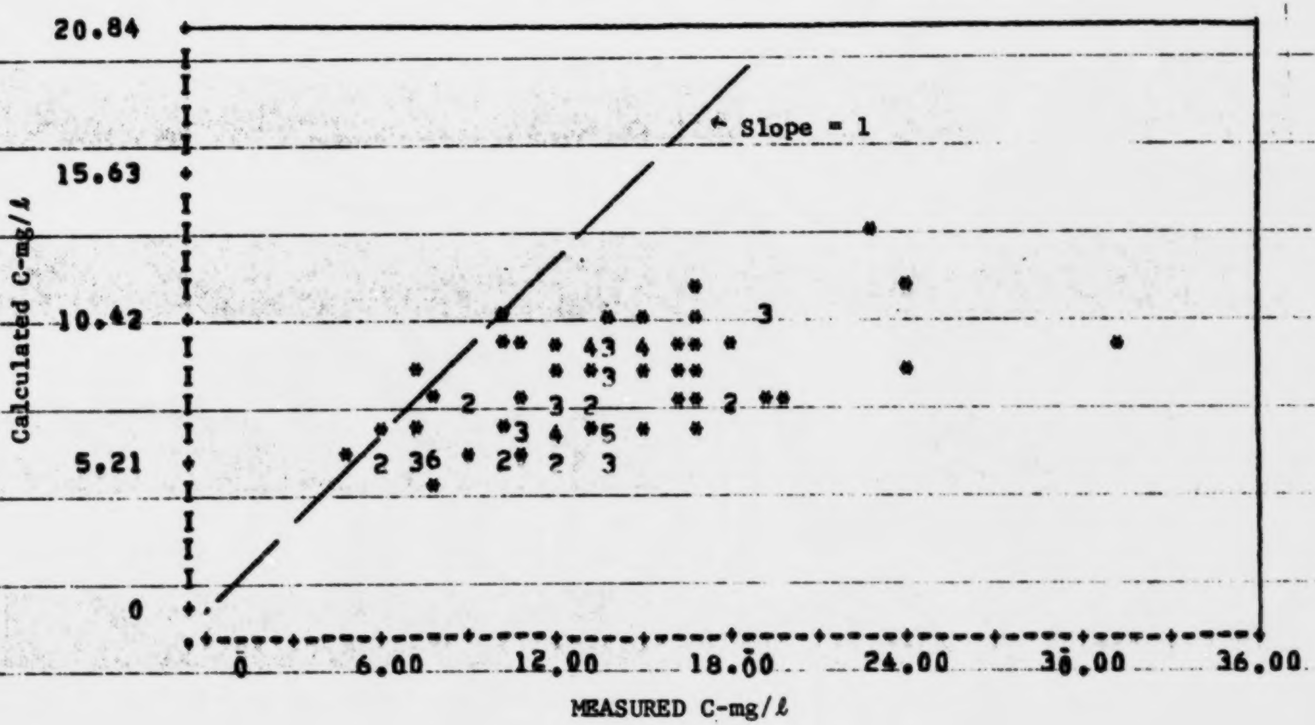


Figure 40. Calculated vs. measured C, Lisle Model, Lake Zurich data.

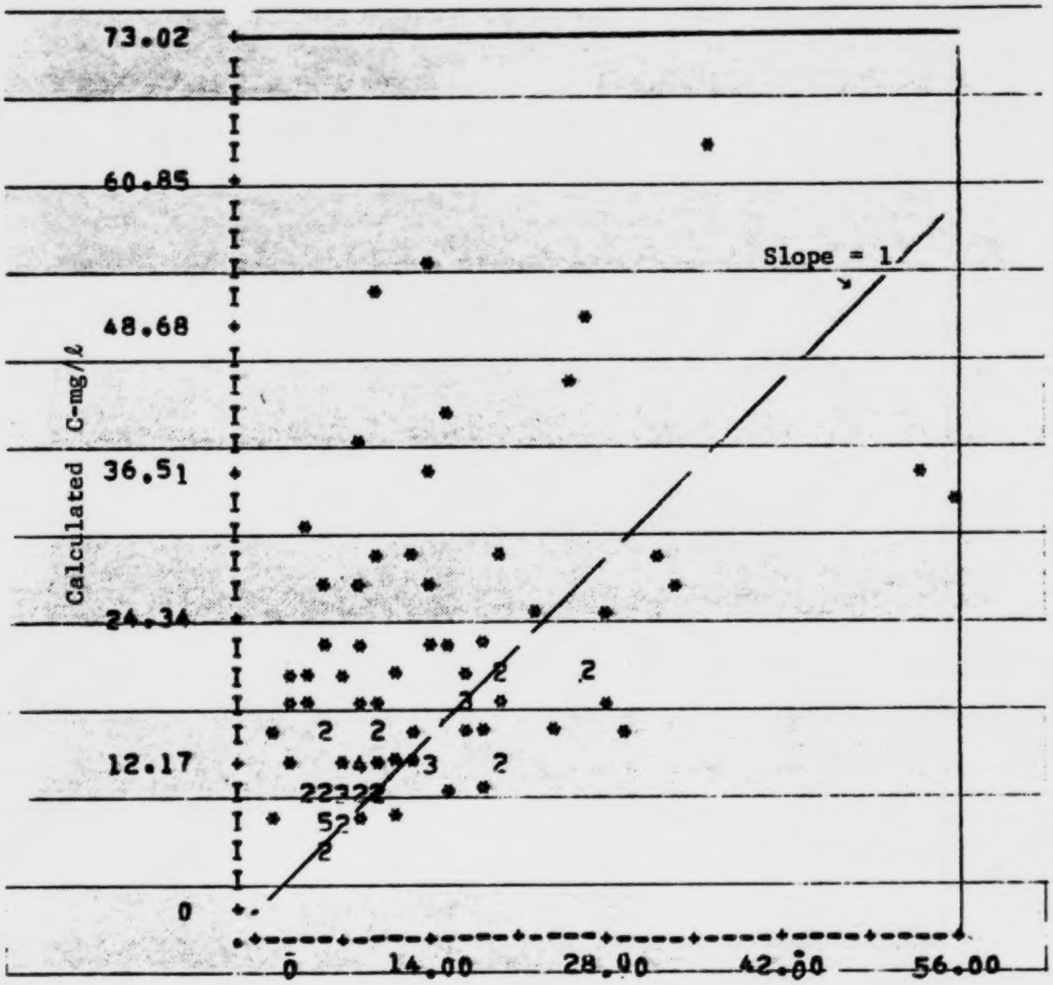


Figure 41. Calculated vs. measured C, Marionbrook Model, Lisle data.

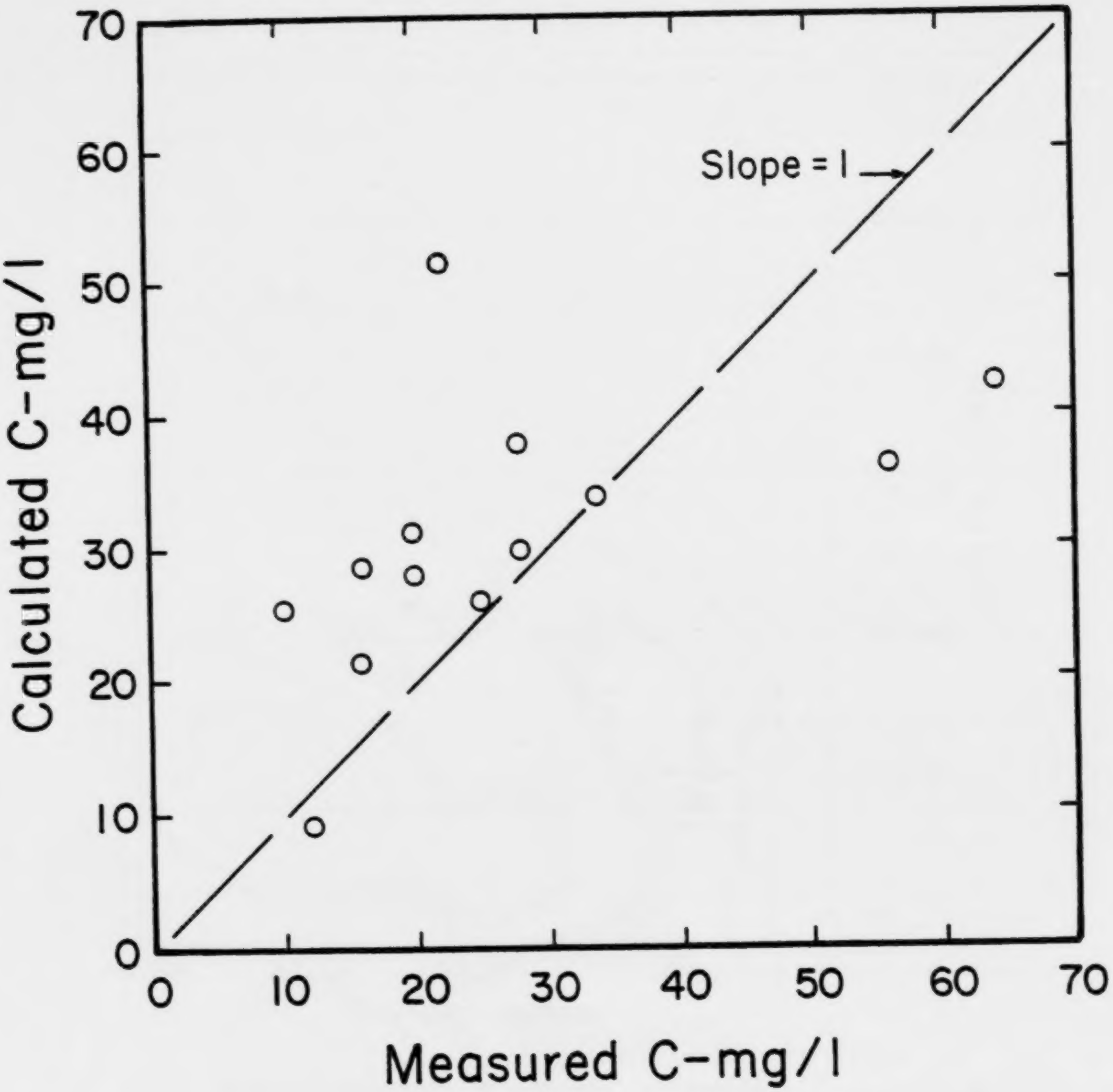


Figure 42. Calculated vs. measured C, Marionbrook Model, Hsiung's data.

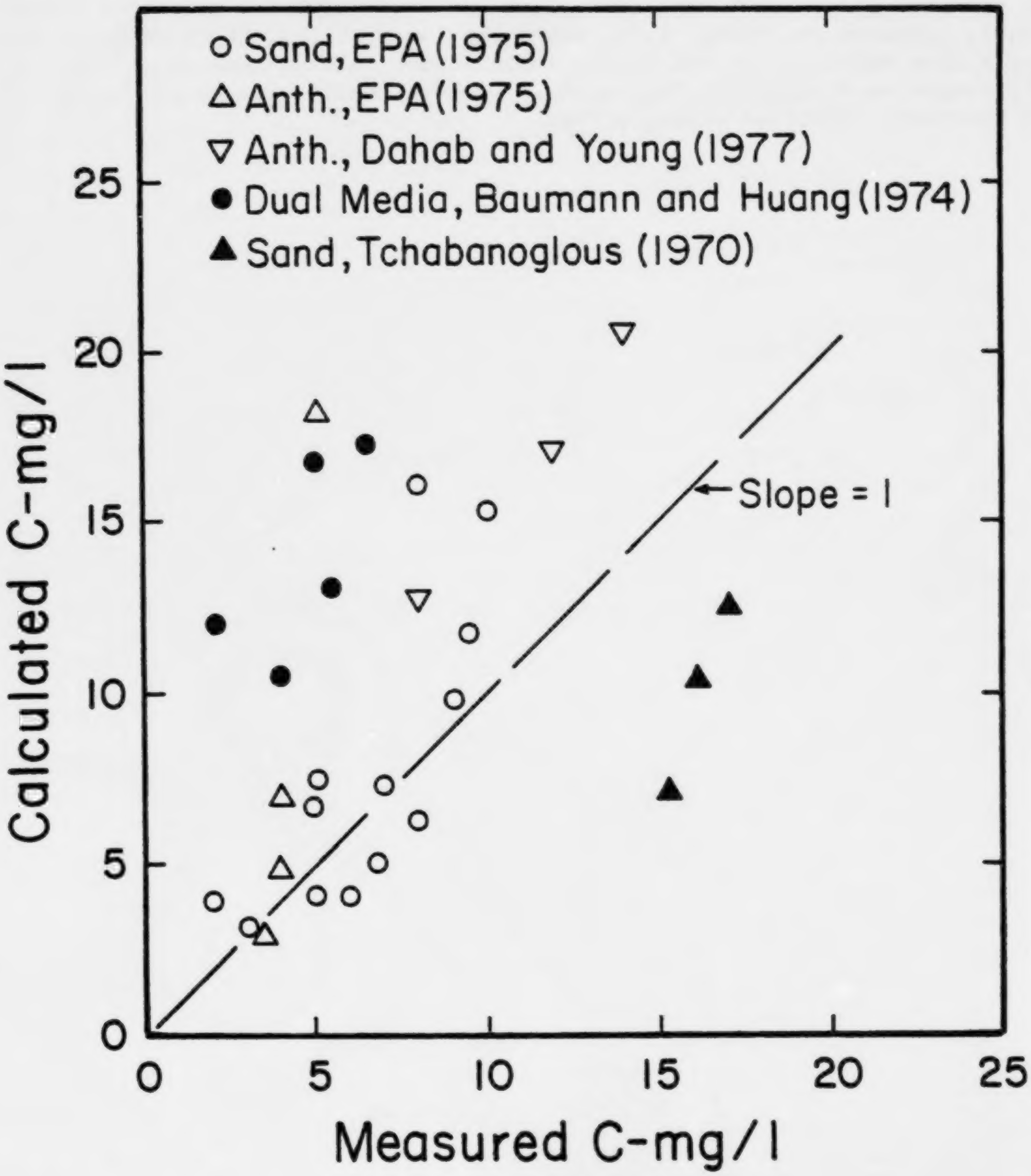


Figure 43. Calculated vs. measured C, Marionbrook Model, published data.

though some improvement in efficiency would be expected for larger depths, the improvement is apparently too small as compared to the influence of other variables. The differences in characteristics of suspensions are most likely the major reason for the variations in performance between plants. However, based on reported pilot studies at equivalent and lower influent suspended solids levels (Baumann and Huang, 1974; Dahab and Young, 1977), it is probable that media size and depth do not have a large effect on mass removal efficiency over the ranges encountered in this study. However, media size in particular has an important effect on clogging rate.

# CHAPTER IX

# RELATIONSHIPS BETWEEN MEASURES OF CHARACTERISTICS OF SECONDARY EFFLUENT SUSPENDED SOLIDS AND THEIR EFFECTS ON FILTER CLARIFICATION EFFICIENCY

## INTRODUCTION

This chapter describes the relationships between measured suspension properties and their individual effects on filter clarification efficiency using data from Phases 2, 3, and 4. Methods used to characterize secondary effluent suspensions were suspended solids concentration, refiltration parameters, and particle size measurements. Attempts to obtain meaningful data on electrophoretic mobility and the optimum cationic polymer dosage necessary to neutralize particle surface charge were not successful.

## RELATIONSHIP BETWEEN MEASURED SUSPENSION CHARACTERISTICS

A summary of mean and ranges for $C_0$, number mean particle size, and refiltration parameters is given in Table 24. Filter influent suspended solids concentrations were, in general, considerably lower during Phase 4 as compared to other phases. A total of 38 samples of filter influent was obtained during Phase 4. Including filters operating at variable flow, 66 data on filter clarification efficiency were obtained. Nine filter influent samples each were obtained at the Addison South plant during Phases 2 and 3, and 19 samples were obtained for the Des Plaines River plant during Phase 3.

### Particle Size Measurements

Typical particle size histograms, expressed as number of particles per $cm^3$ for each size class, are shown in the following figures:

| Figure | Phase | Plants |
|---|---|---|
| 44 | 3, 4 | Addison South |
| 45 | 3, 4 | Des Plaines River |
| 46 | 4 | Addison North, Barrington |
| 47 | 4 | Lake Zurich, Lisle |
| 48 | 4 | Marionbrook, Romeoville |

Very few particles were larger than 100 μm. Larger floc particles were observed at the secondary sedimentation tank overflow weirs but were broken up by turbulence in flow to the filters and by the sample preparation technique used. Secondary effluent flows to the filters by gravity at the Barrington, Des Plaines River, and Romeoville plants, and is pumped for other plants.

Table 24. Summary of particle size and refiltration data.

|  | No. of Cases | $C_o$-mg/ℓ |  | $d_{nm}$-μm |  | R |  | G |  | E |  |
|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | Mean | Range | Mean | Range | Mean | Range | Mean | Range | Mean | Range |
| Hsiung's Data | 13 | 82 | 20-150 | - | - | 3.8 | 1.9-8.8 | 2.2 | 1.4-2.5 | 1.82 | 1.3-2.1 |
| Phase 2 |  |  |  |  |  |  |  |  |  |  |  |
| Addison South | 9 | 143 | 41-293 | - | - | 8.6 | 3.0-16 | 1.3 | 0.8-1.9 | 1.60 | 1.3-1.8 |
| Phase 3 |  |  |  |  |  |  |  |  |  |  |  |
| Addison South | 9 | 65 | 47-104 | 8 | 7-10 | 3.8 | 2.9-4.9 | 1.8 | 1.6-2.0 | 1.67 | 1.6-1.8 |
| Des Plaines River | 19 | 58 | 42-89 | 18 | 13-22 | 7.3 | 4.6-12 | 1.5 | 1.2-2.0 | 1.71 | 1.6-1.8 |
| Phase 4 |  |  |  |  |  |  |  |  |  |  |  |
| All Data | 38 | 22 | 9-47 | 16 | 8-38 | 3.8 | 1.2-11 | 1.7 | 1.4-2.5 | 1.61 | 1.3-1.9 |
| Addison North | 6 | 19 | 14-29 | 16 | 8-26 | 6.2 | 4.4-11 | 1.7 | 1.5-2.1 | 1.74 | 1.6-1.8 |
| Addison South | 6 | 35 | 20-47 | 12 | 9-20 | 5.6 | 2.1-8.4 | 1.8 | 1.6-2.2 | 1.75 | 1.7-1.8 |
| Barrington | 7 | 18 | 9-38 | 17 | 8-30 | 3.6 | 1.8-5.2 | 1.7 | 1.5-1.8 | 1.58 | 1.5-1.8 |
| Des Plaines River | 6 | 22 | 17-28 | 16 | 11-18 | 2.9 | 1.7-4.8 | 1.9 | 1.7-2.5 | 1.64 | 1.5-1.9 |
| Lake Zurich | 4 | 18 | 13-24 | 12 | 8-18 | 1.8 | 1.2-2.8 | 1.7 | 1.4-2.1 | 1.40 | 1.3-1.5 |
| Lisle | 2 | 14 | 14,14 | 12 | 11,13 | 2.6 | 2.2,2.9 | 1.4 | 1.4,1.4 | 1.38 | 1.4,1.4 |
| Marionbrook | 2 | 42 | 39,46 | 12 | 11,14 | 2.3 | 2.1,2.6 | 1.9 | 1.8,2.1 | 1.60 | 1.6,1.6 |
| Romeoville | 5 | 13 | 9-20 | 22 | 10-38 | 3.1 | 2.1-6.4 | 1.7 | 1.5-2.1 | 1.56 | 1.4-1.7 |

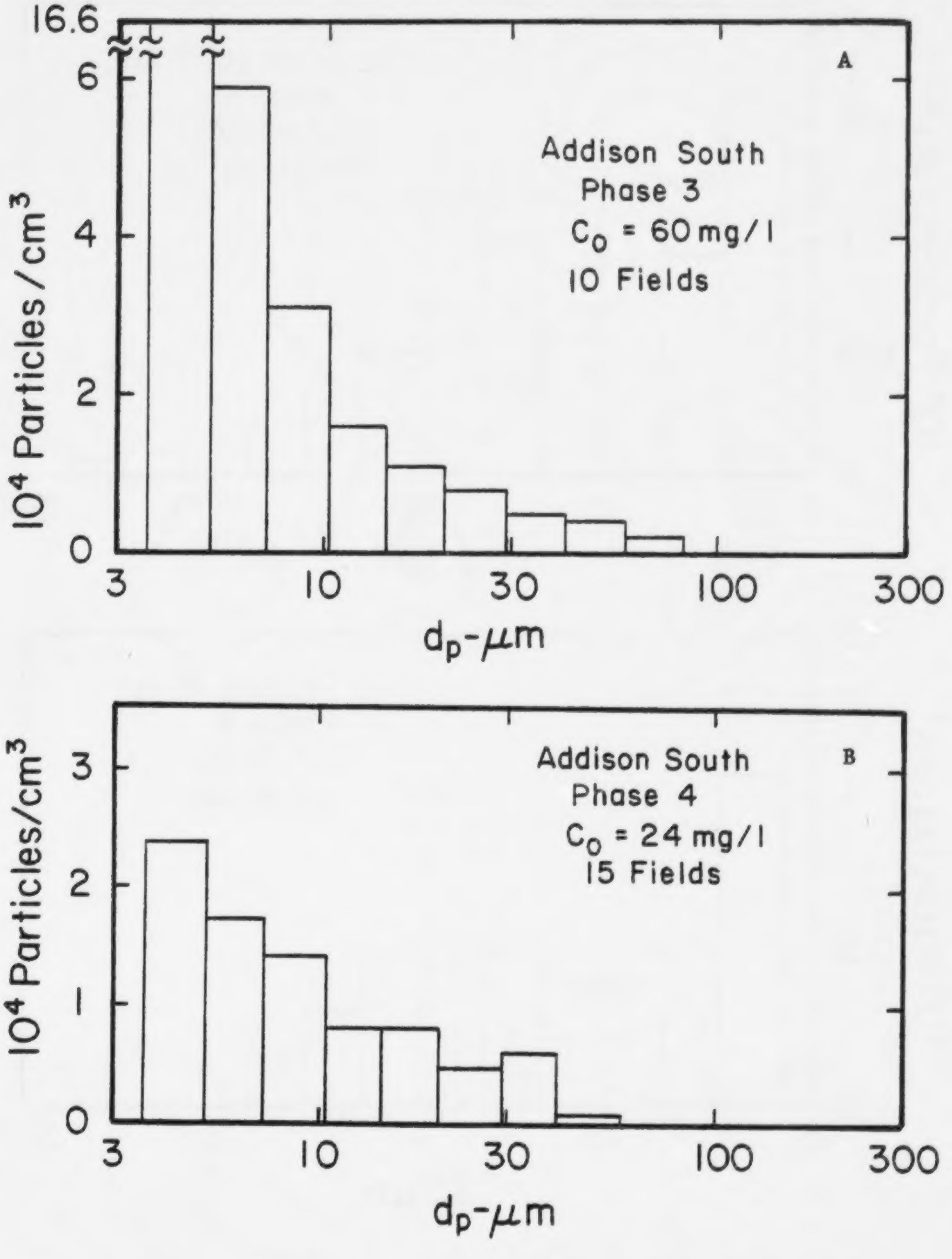


Figure 44. Particle size histogram, Addison South -Phases 3 and 4.

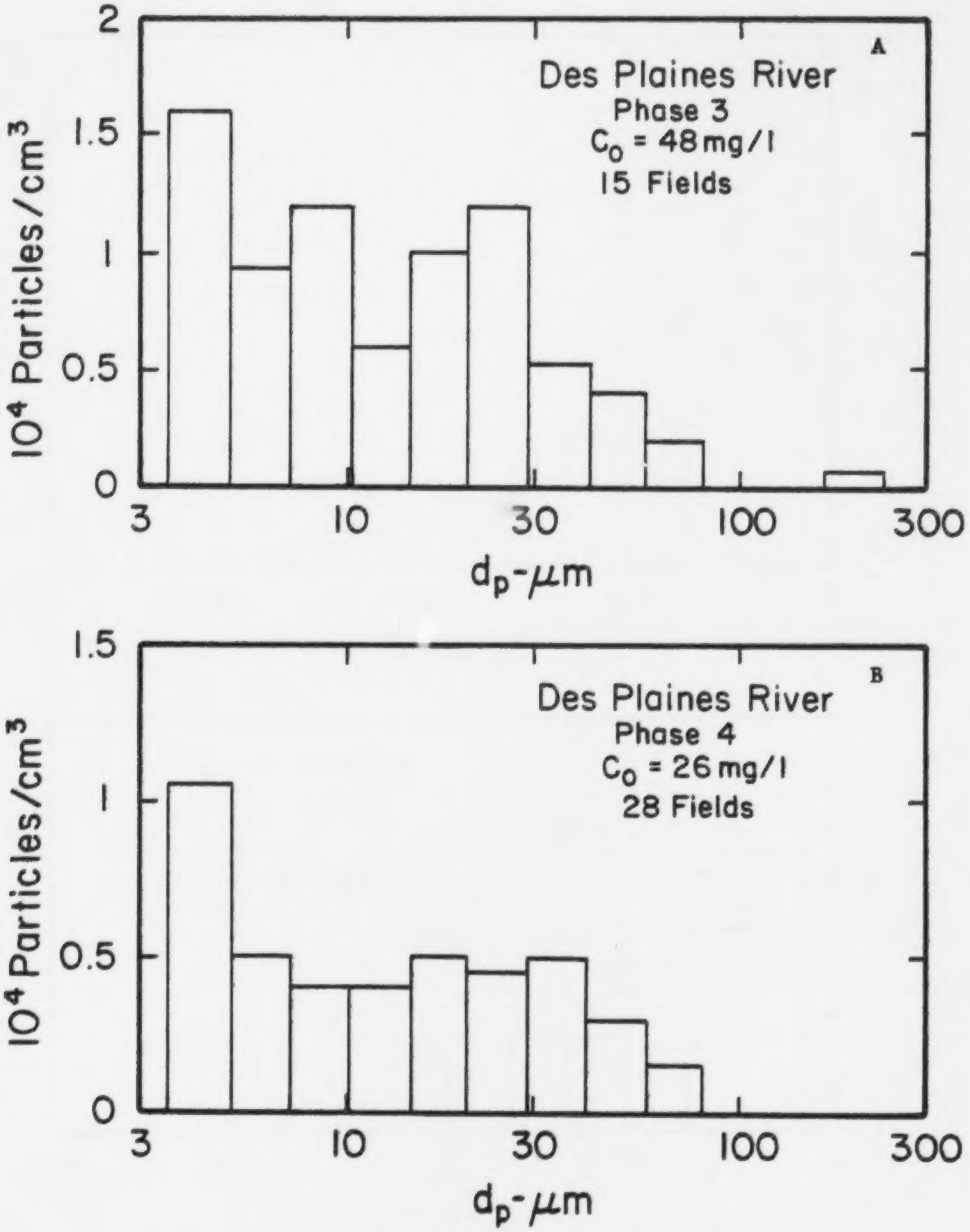


Figure 45. Particle size histogram, Des Plaines River - Phases 3 and 4.

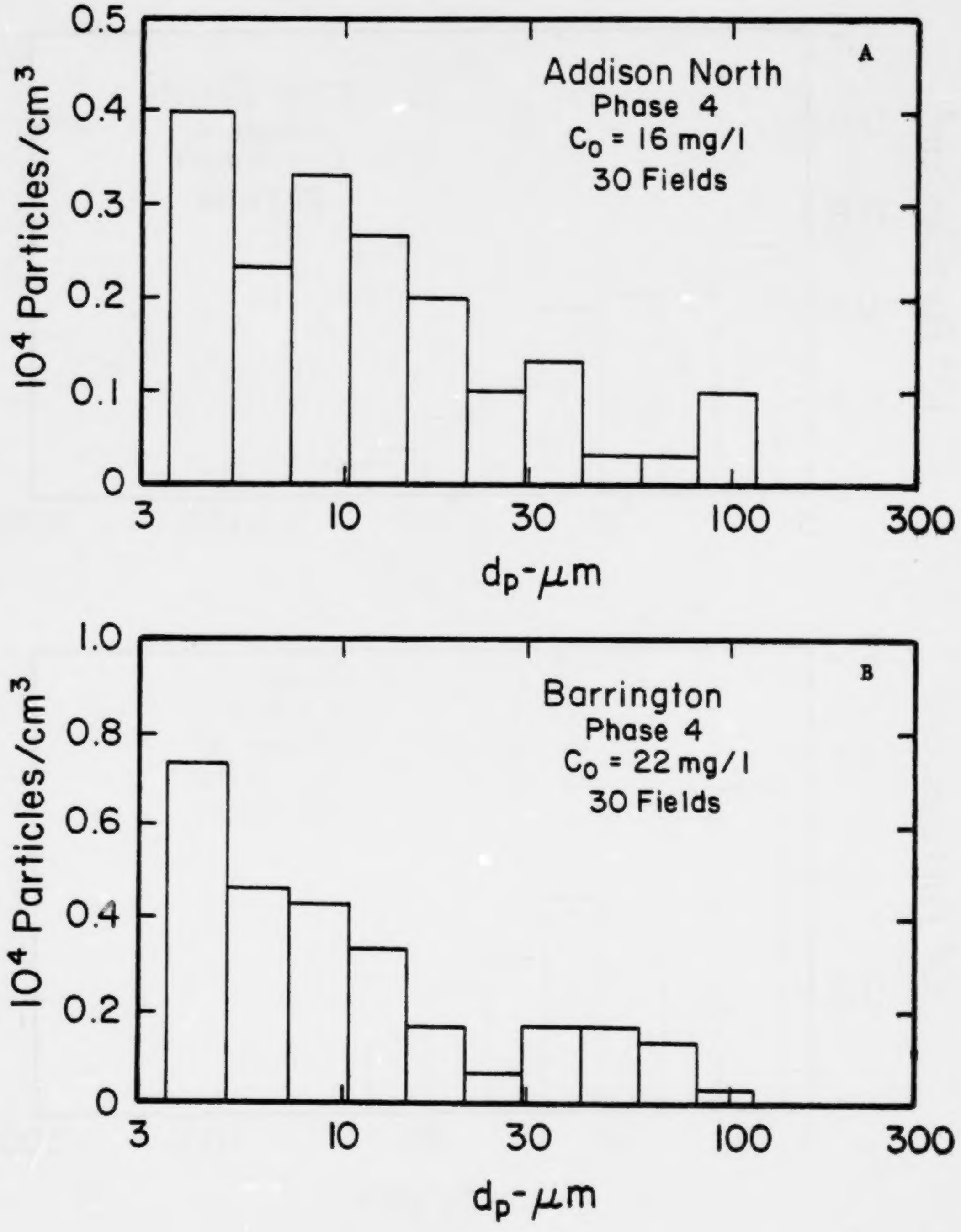


Figure 46. Particle size histogram, Addison North and Barrington - Phase 4.

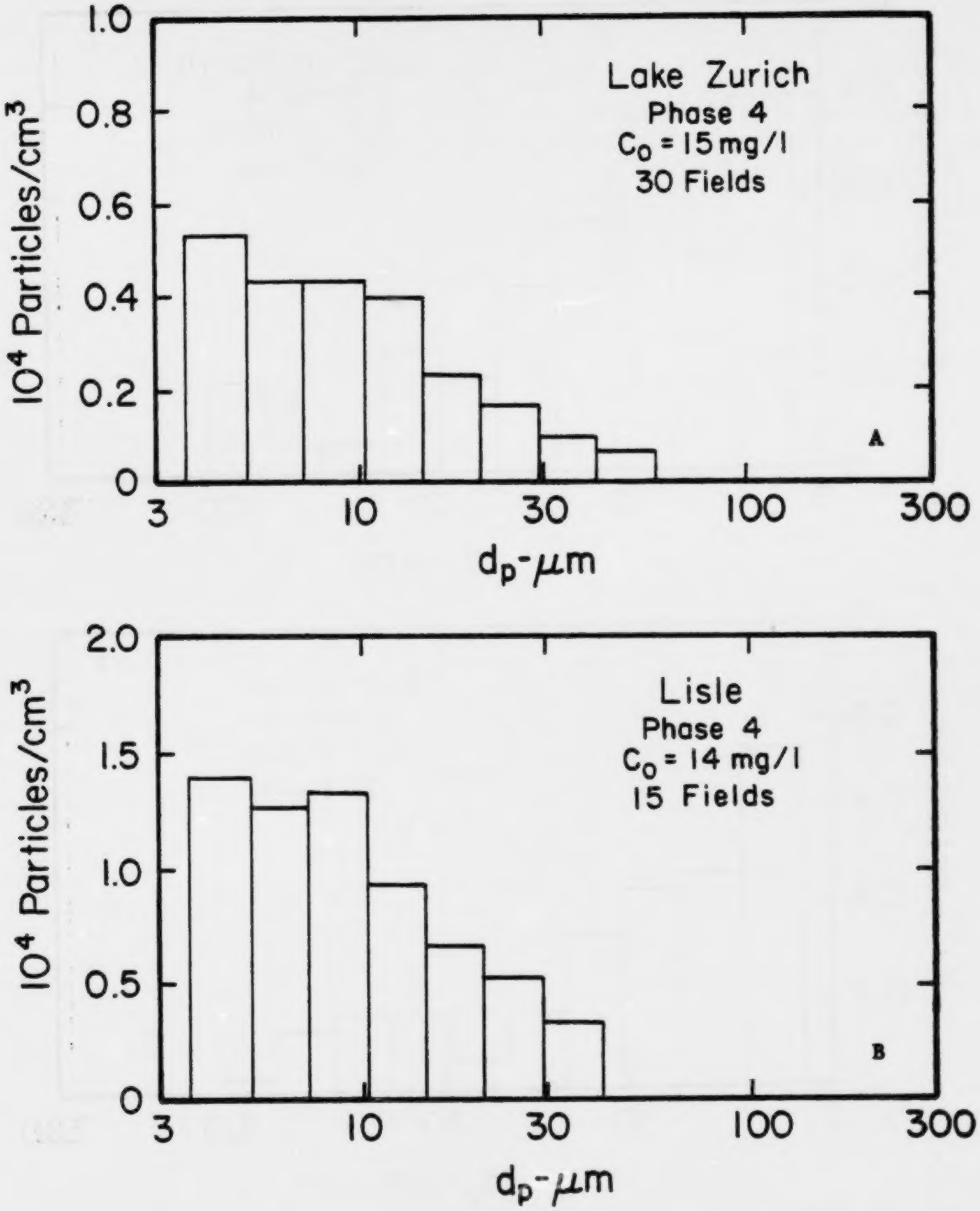


**Figure 47. Particle size histogram, Lake Zurich and Lisle - Phase 4.**

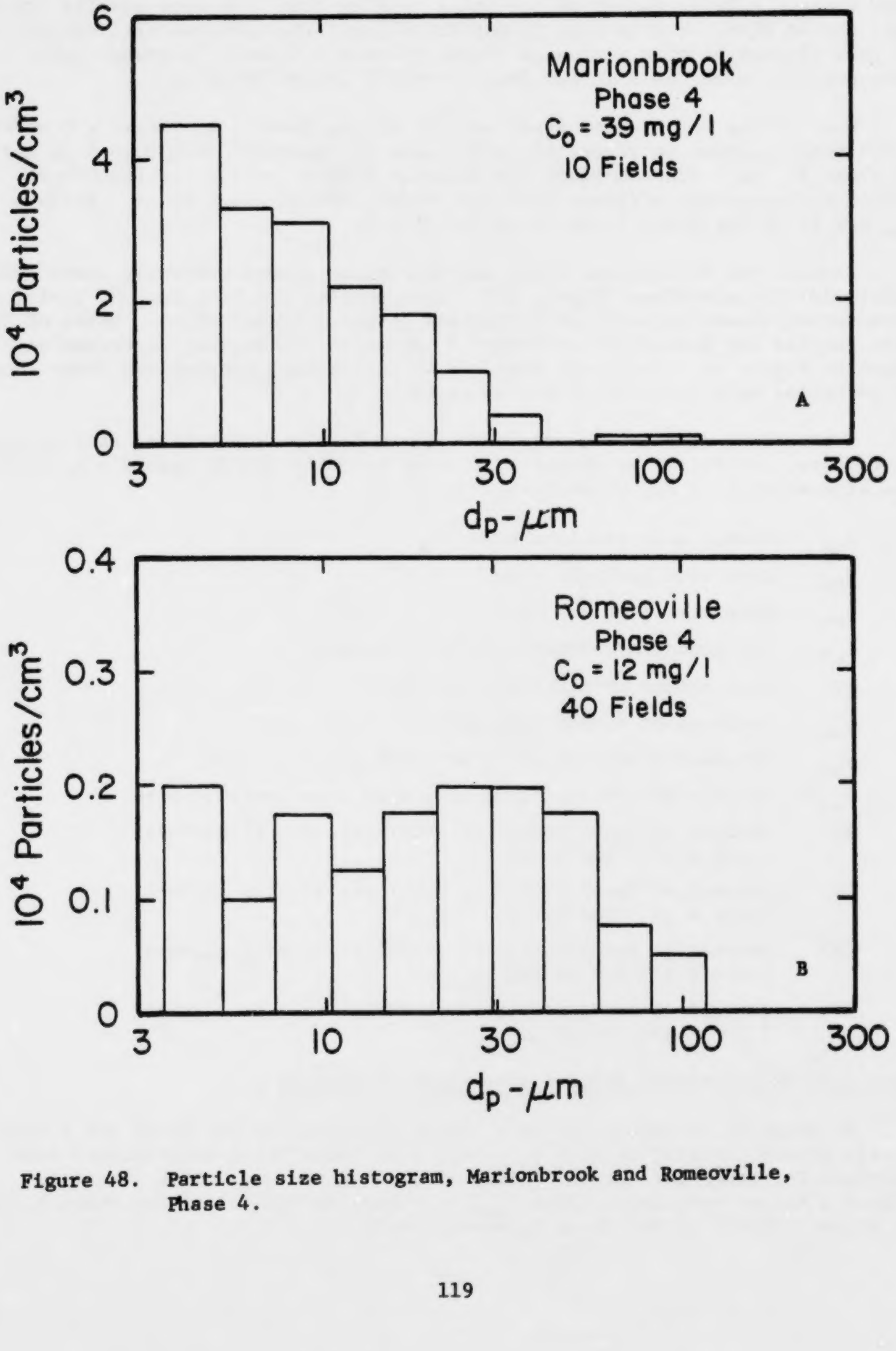


Figure 48. Particle size histogram, Marionbrook and Romeoville, Phase 4.

The Addison South data in Figure 44 show a unimodel distribution for this size range. A large number of particles smaller than 3 μm were usually present. This can be attributed in part to the trickling filter process effluent which is less flocculent than activated sludge process effluent. Average number mean particle size was 8 μm for Phase 3 and 12 μm for Phase 4.

Most of the Des Plaines River samples during Phase 3 exhibited a bimodal distribution, shown in Figure 45, with peaks in the range from 3 to 5 μm and at about 30 μm. Tchobanoglous and Eliassen (1970) found a similar distribution for secondary effluent with the second peak at about 80 μm. Average $d_{nm}$ was 18 μm for Phase 3 and 16 μm for Phase 4.

Samples for the Addison North and Barrington plants generally showed weak multimodal distributions (Figure 46). Most samples for Lake Zurich, Lisle, and Marionbrook showed unimodal distributions (Figures 47 and 48). Three of the five samples for Romeoville exhibited a random or rectangular distribution, shown in Figure 48. For these samples, 40 fields were counted and fewer than 10 particles were found in each size class.

A bivariate correlation matrix for particle size statistics, refiltration parameters, and filter performance is given in Table A-3 in Appendix A. Particle size statistics are shown below.

| | |
|---|---|
| $d_{nm}$ | Number mean particle size |
| $d_{am}$ | Area mean particle size |
| $d_{mm}$ | Mass mean particle size |
| $d_{4M}$ | 4th moment of number mean particle size |
| NT | Mean number of particles per field |
| $\sigma^2_{nm}$ | Variance of number mean particle size |
| $\sigma_{nm}$ | Standard deviation of number mean particle size |
| $\sigma_{nm}/\bar{x}$ | Coefficient of variation of number mean particle size |
| %S1 | Percent of total number of particles in size classes 1 and 2 (4.2 and 6 μm) |
| %S2 | Percent of total number of particles in size classes 3 and 4 (8.5 and 12 μm) |
| %S3 | Percent of total number of particles in size classes 5 and 6 (17 and 24 μm) |
| %S4 | Percent of total number of particles in size classes 7 to 12 (30 to 192 μm) |

## Bivariate Relationships Between Suspension Properties

As would be expected, the mean number of particles per field had a relatively strong correlation with $C_o$. Very poor correlation coefficients were obtained for other parameters. Plots of R and E vs. $\sigma_{nm}$, which generally showed a better correlation than $d_{nm}$, are shown in Figures 49 for Phase 3, and in Figures 50 and 51 for Phase 4, respectively.

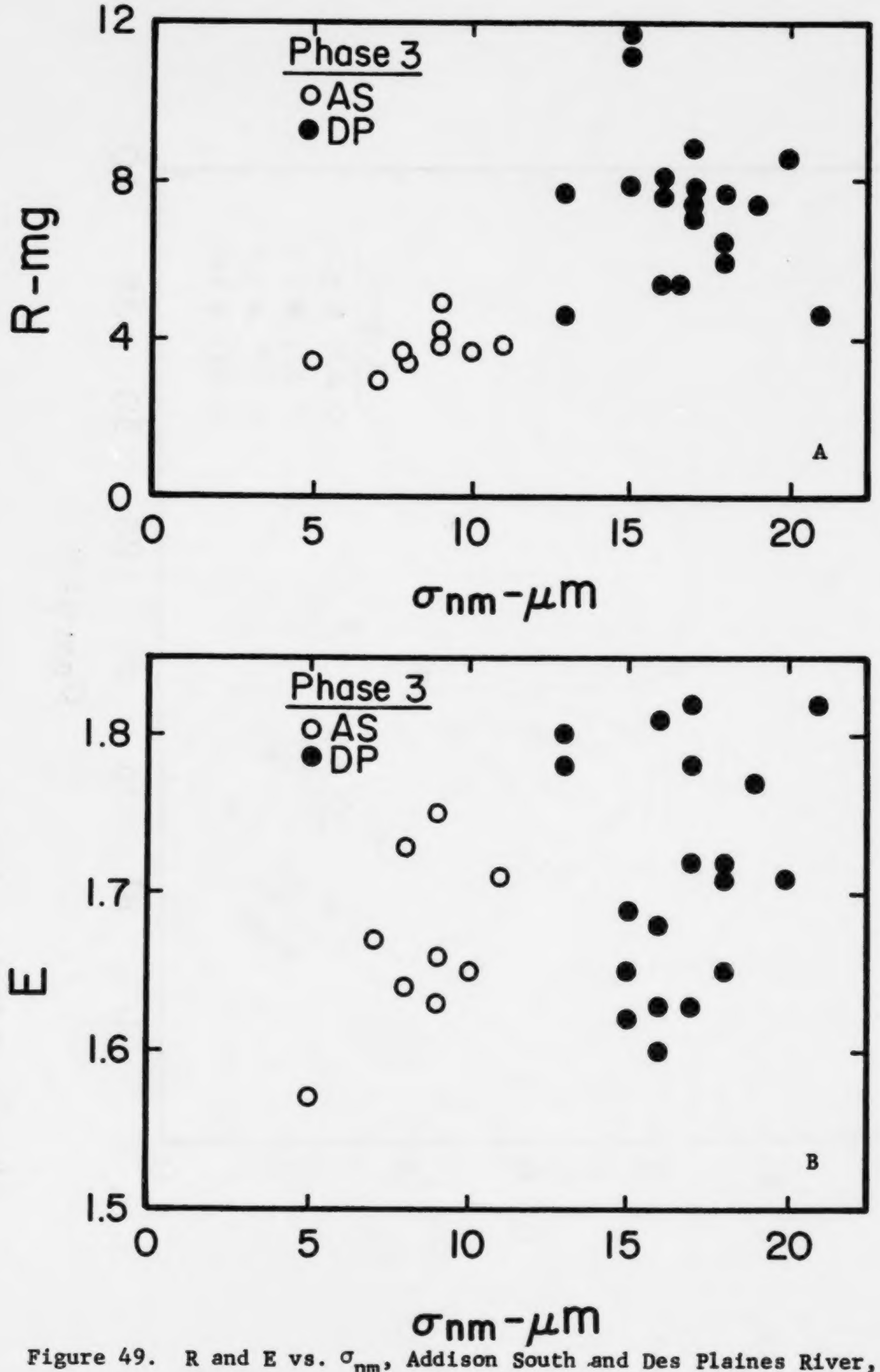


Figure 49. R and E vs. $\sigma_{nm}$, Addison South and Des Plaines River, Phase 3

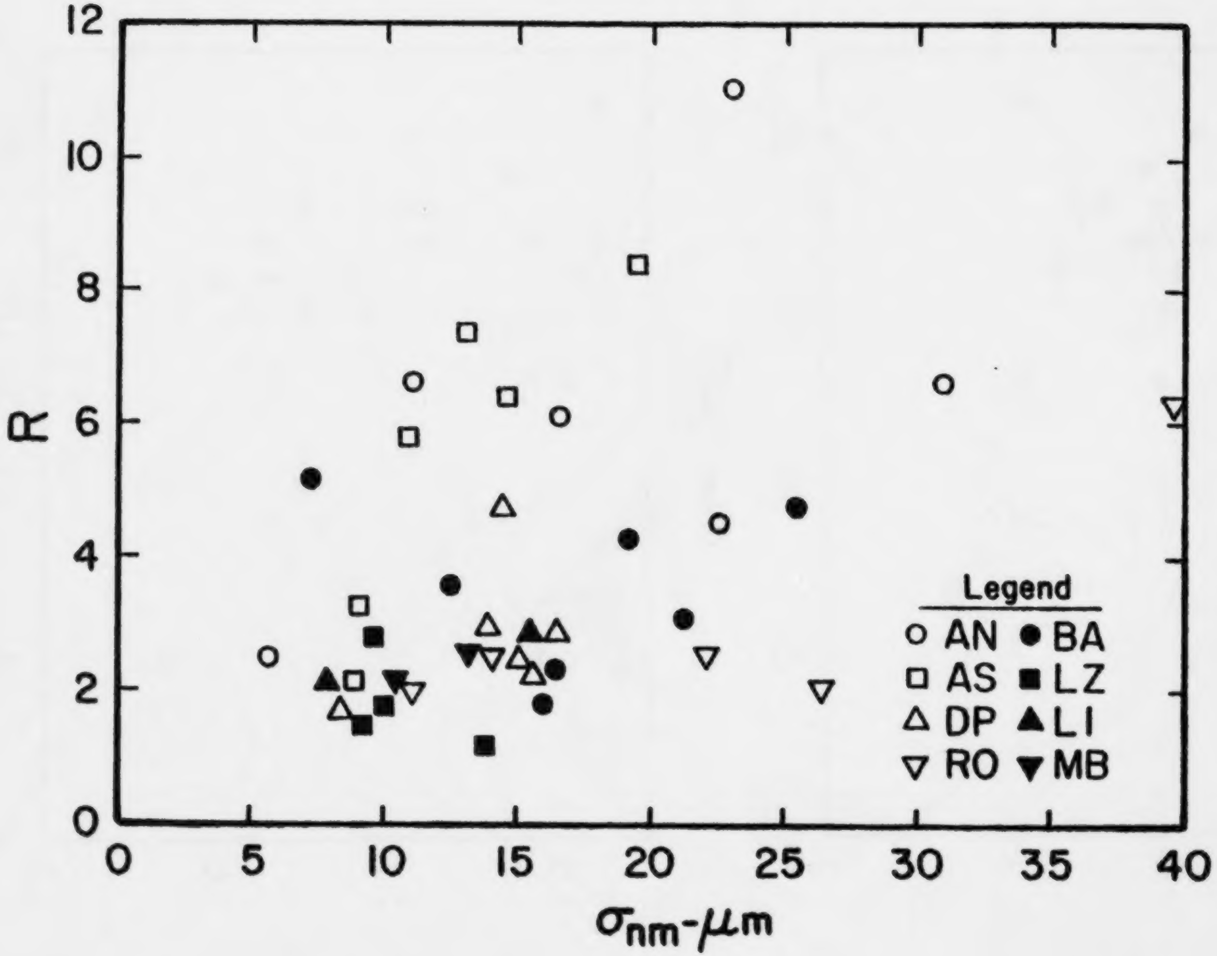


Figure 50. R vs. $\sigma_{nm}$ - Phase 4.

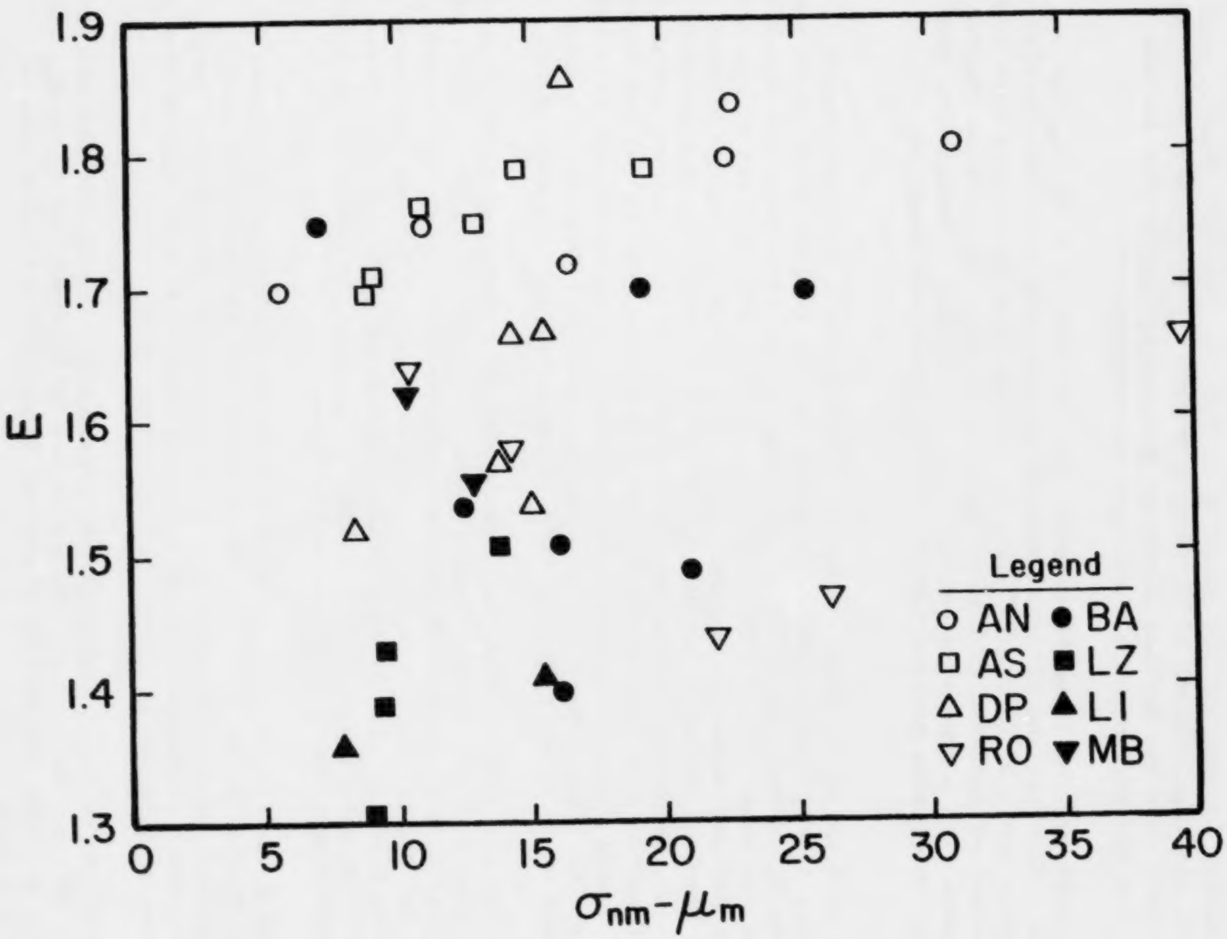


Figure 51. E vs. $\sigma_{nm}$ - Phase 4.

For Phase 3 data, both R and E appear to increase for larger values of $\sigma_{nm}$. This would be expected since large values for $\sigma_{nm}$ correspond to higher $d_{nm}$, and theory suggests that both R and E should increase with particle size. No trend is apparent for the Des Plaines data for Phase 3.

Wide scatter is apparent for the plot of R vs. $\sigma_{nm}$ for all Phase 4 data in Figure 50, although a trend of increasing R with $\sigma_{nm}$ is present (r = 0.40). Individual plant data for Addison North and Romeoville, and except for one outlying point for Barrington, show a stronger correlation.

From Figure 51, no trend is apparent for the plot of E vs. $\sigma_{nm}$ for all Phase 4 data. However, the Addison South plant data show a strong correlation over the narrow range of E from 1.7 to 1.8. The Addison North data also show a definite trend of increase in E with increase of $\sigma_{nm}$. As shown in Chapter IV E is determined with a precision better than ± 2 percent. Considering the error bounds, the trends present for the Addison North and South are not as strong.

A plot of R vs. $C_o$ is shown in Figure 52 for Hsiung's data and Phases 2 and 3. A very strong correlation is apparent for the Addison South plant for Phase 2 where $C_o$ exceeded 200 mg/ℓ for three of the nine runs, and exceeded 100 mg/ℓ for six runs. These high SS levels resulted from failure of the activated sludge process secondary sedimentation tanks where the sludge blanket reached the level of the effluent weirs. Although no particle size measurements were made, large floc particles were observed in the secondary effluent. A similar situation with high sludge blanket levels occurred at the Des Plaines River plant during Phase 3, although the sedimentation tanks did not fail completely. For Des Plaines River, R is considerably higher than for the other data but shows no trend with $C_o$. No trend is apparent for the other data.

Except for the Addison South and Barrington plant data, no trend is apparent for the plot of R vs. $C_o$ for Phase 4 data, shown in Figure 53 . Plots of $d_{nm}$ and $\sigma_{nm}$ vs. $C_o$ are shown in Figure 54 where a relatively strong correlation is apparent for the few data. Therefore, Figure 53 actually shows the correlation between R and $\sigma_{nm}$ for Addison South. It can be concluded then that R is not related to $C_o$ except when higher values of $C_o$ indicate carryover of large floc particles from secondary sedimentation tanks.

Plots of E vs. $C_o$ are shown in Figure 55 for Hsiung's data and Phases 2 and 3 are in Figure 56 for Phase 4. Phase 2 data for Addison South show a strong correlation of E to $C_o$ which can be attributed to carryover of large floc from secondary sedimentation tanks, as discussed for R vs. $C_o$. Hsiung's data also show an increase of E with larger values of $C_o$.

In Figure 56, E shows a very strong correlation with $C_o$ for the Addison South data. This may also be attributed to the relationship of $C_o$ to $d_{nm}$ and $\sigma_{nm}$ in Figure 54. The Des Plaines River and Barrington data also show an increase of E with $C_o$.

If the error bounds for E are considered, the correlations present in Figures 55 and 56 would be weakened. The consistent trends for the plots of $d_{nm}$ and $\sigma_{nm}$ vs. $C_o$ and E vs. $C_o$ for the Addison South Phase 4 data suggest

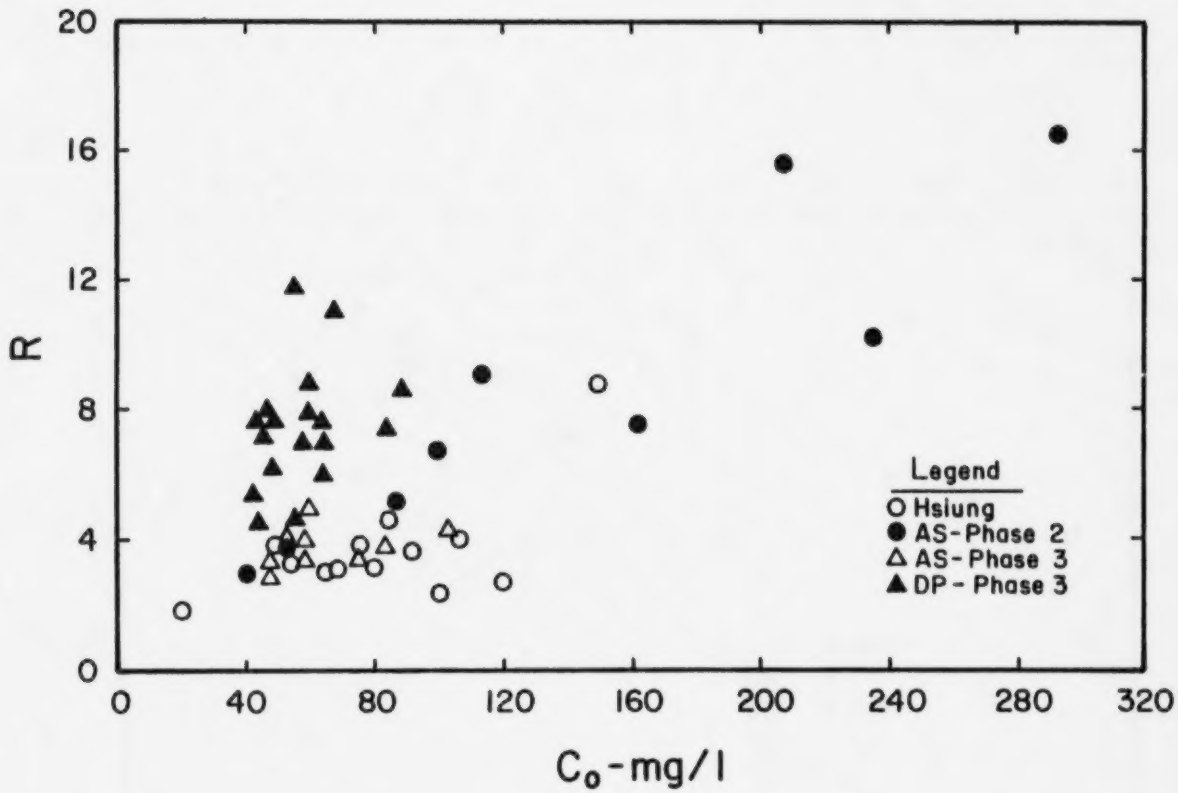


Figure 52. R vs. $C_o$, Hsiung's data - Phases 2 and 3.

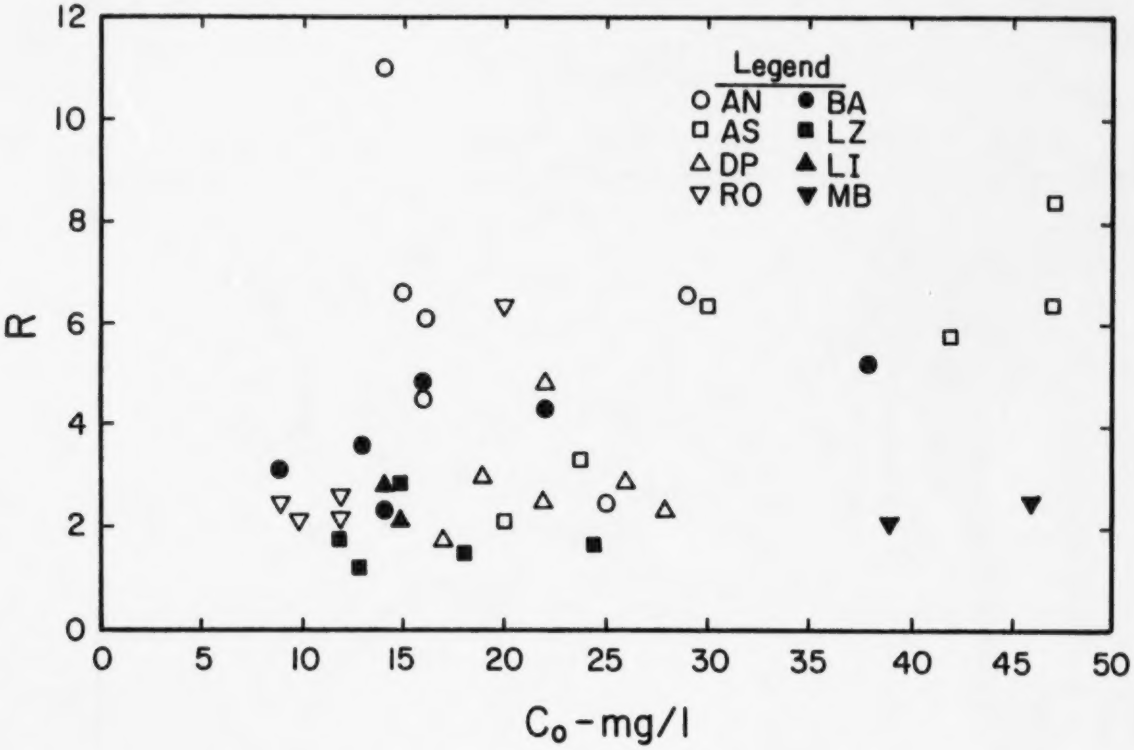


Figure 53. R vs. $C_o$ - Phase 4.

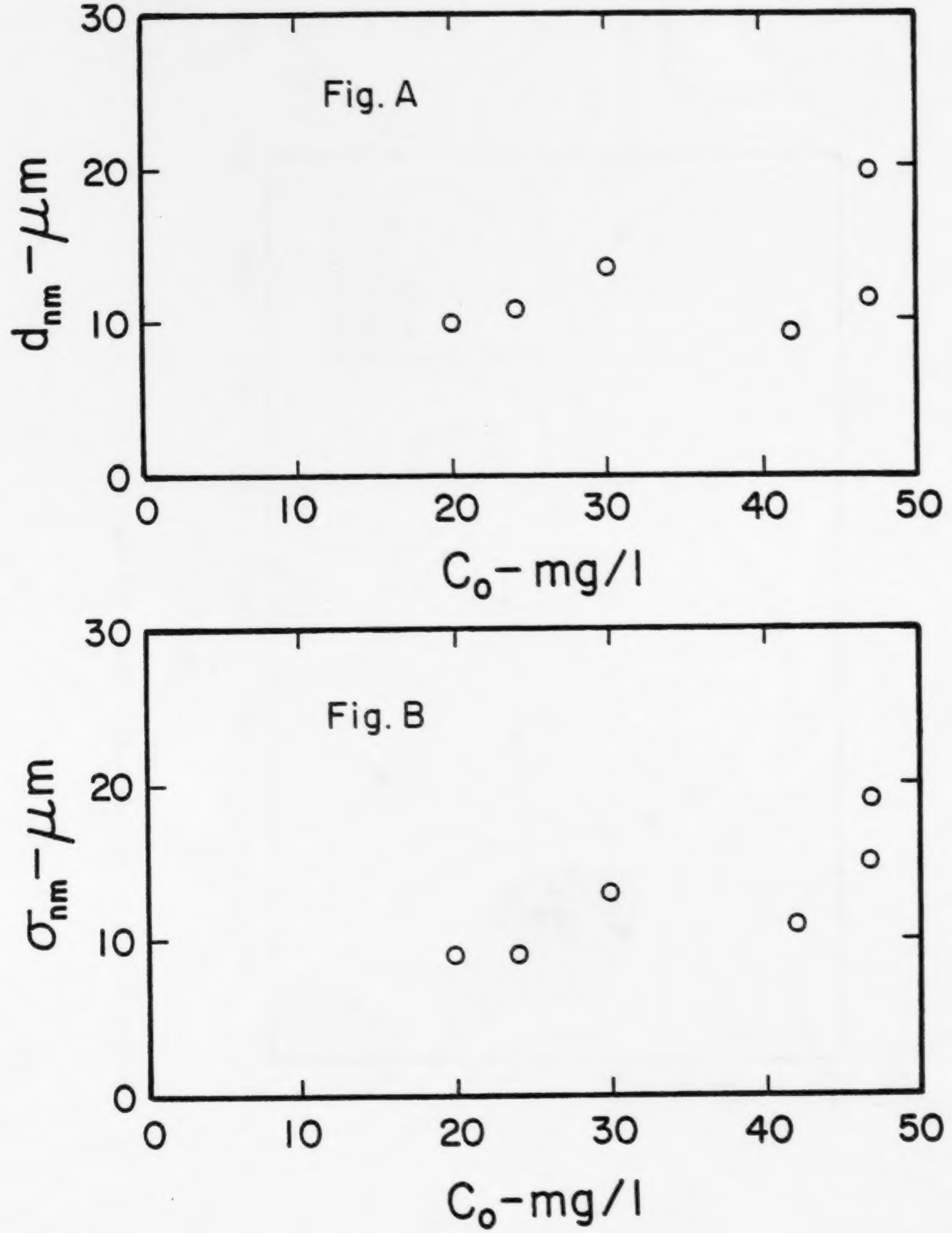


Figure 54. $d_{nm}$ and $\sigma_{nm}$ vs. $C_o$, Addison South - Phase 4.

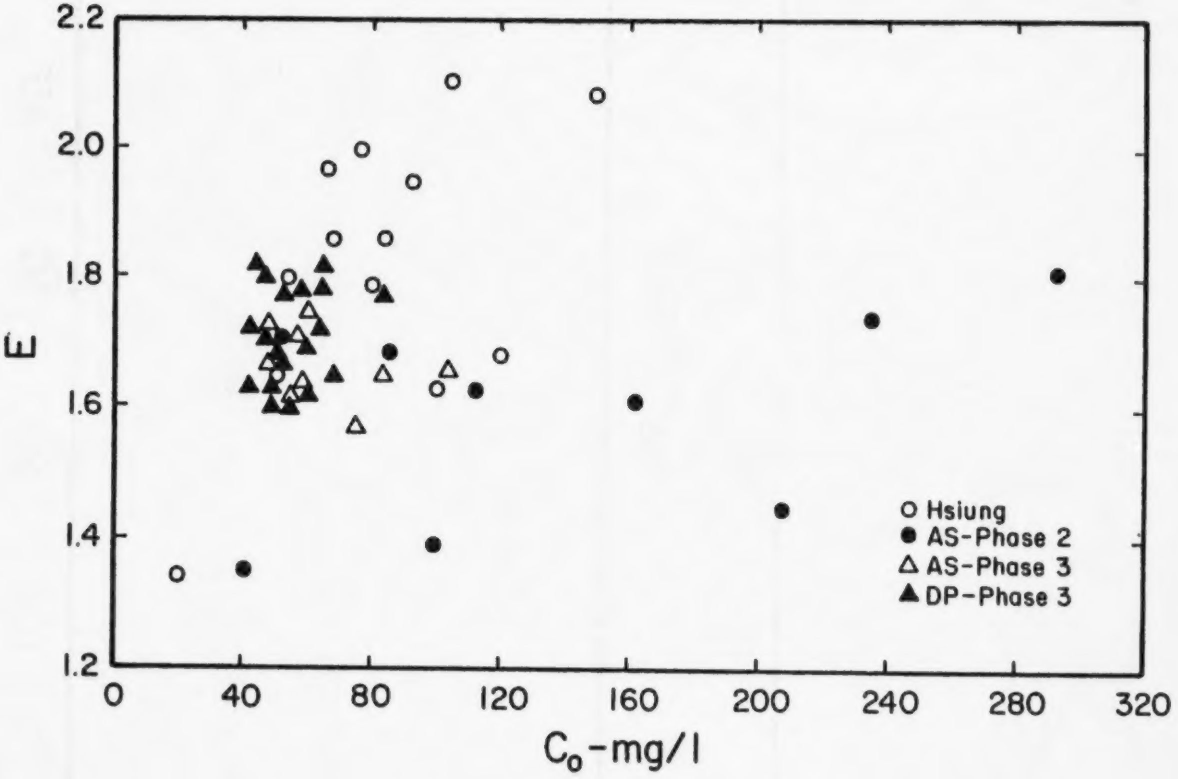


Figure 55. E vs. $C_o$, Hsiung's data - Phases 2 and 3.

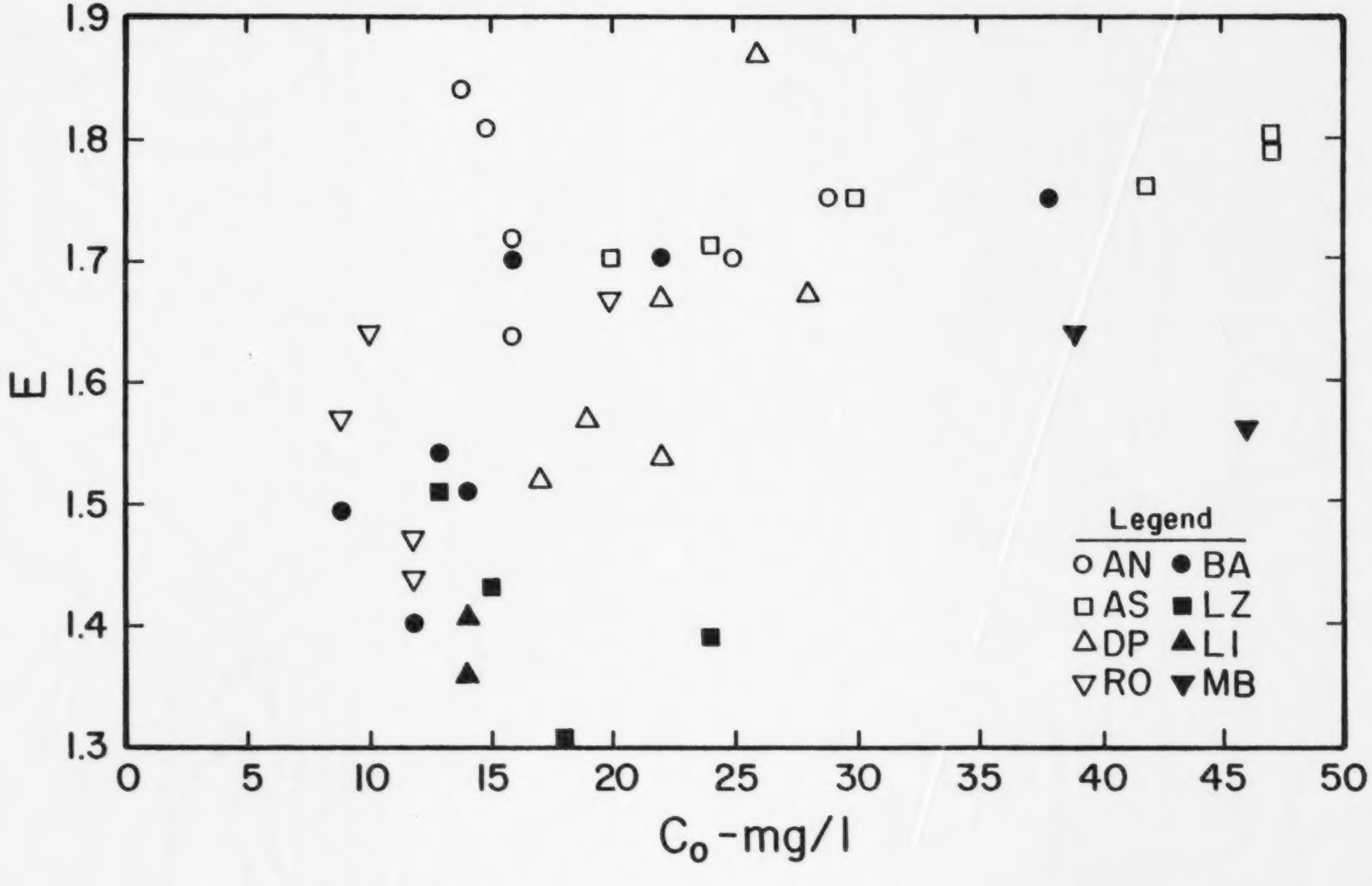


Figure 56. E vs. $C_o$ - Phase 4.

that E may, in fact, be determined to a precision considerably better than ± 2 percent. The method used to estimate the error bounds in Chapter IV is considered to be conservative.

## BIVARIATE RELATIONSHIPS OF FILTER PERFORMANCE TO SOLIDS LOADING AND SUSPENSION CHARACTERISTICS

A bivariate correlation matrix of filter performance vs. refiltration parameters, flow rate, influent suspended solids, solids loading, and number mean particle size is given in Table 25. If straining was believed to be the dominant particle collection mode, good correlations of log $C/C_0$ and $C/C_0$ with R and E would be obtained. The parameter G exhibited poor correlations. Number mean particle size correlated well with some individual plant data but did not show good correlations between plants. Effluent suspended solids (C) showed a strong dependence on solids loading for data sets where straining was not considered to be the dominant particle collection mode.

### Solids Loading

Plots of C vs. solids loading for Phases 2 and 3 for Addison South are shown in Figure 57. Wider scatter is apparent for Phase 2 compared to the strong correlation for Phase 3. Mean $d_{nm}$ for Phase 3 was 8 μm with a range of 7 to 10 μm, the smallest particle diameters measured in Phases 2 and 3. Headloss buildup was very rapid during Phase 2. For the three-hour runs in Phase 3, headloss buildup was very low and decreased during several runs because of decreases in plant flow. Thus the apparent dominant particle collection mode was straining for Phase 2 and in-depth filtration for Phase 3.

During Phase 3 at the Des Plaines River plant, influent suspended solids levels were higher than normal due to solids carryover from final clarifiers. Except for four of the 19 one-hour runs, backwash mechanisms were operating continuously making it difficult to define an appropriate run length. Backwash is initiated for these sand filters when the headloss exceeds 3 in. On several occasions the maximum headloss limit of 15 in. was exceeded and the filters failed to handle the process flow.

Plots of C vs. headloss and solids loading are shown in Figures 58A and 58B, respectively. Figure 58A shows a strong correlation of C with headloss. In Figure 58B, data are equally segmented into "low" and "high" headloss levels. Although it would be expected that surface straining would be the dominant particle collection mode for sand filters, the higher C values for "high" headloss in Figure 58B suggest that solids breakthrough was also occurring. The increase in C for high headloss is probably caused by sloughing of particles at or near the top of the filter media and deeper penetration of floc particles. Another factor that may be significant is the high localized filtration rate in sections of the filter media that had just been backwashed by the traveling mechanism.

Plots of C vs. solids loading for Phase 4 are shown in the following figures:

Table 25. Bivariate correlation coefficients for filter performance, Hsiung's data - Phases 2, 3 and 4.

|  | Hsiung's Data | DP3 | Phase 2 |  |  | Phase 3 |  |  | Phase 4 |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  | AVL | AVM | AVH | AVL | AVM | AVH | ALL | MED.Q |
| No. of Cases | 13 | 19 | 9 | 9 | 9 | 9 | 9 | 9 | 66 | 38 |
| Log $C/C_o$ to: |  |  |  |  |  |  |  |  |  |  |
| R | -.67 | -.30 | -.72 | -.85 | -.84 | -.37 | -.48 | -.44 | -.62 | -.57 |
| G | -.64 | .16 | .23 | .29 | .22 | .71 | .14 | 0 | -.04 | -.08 |
| E | -.82 | -.19 | -.49 | -.53 | -.57 | .42 | -.47 | -.29 | -.70 | -.65 |
| C to: |  |  |  |  |  |  |  |  |  |  |
| Q | - | .65 | .21 | .45 | .28 | .42 | .48 | .78 | .32 | .05 |
| $C_o$ | .51 | .14 | .47 | .71 | .48 | .45 | .57 | .80 | .60 | .71 |
| $C_oQ$ | - | .51 | .50 | .77 | .54 | .48 | .53 | .81 | .63 | .47 |
| R | -.23 | -.01 | .17 | .55 | .35 | .07 | -.12 | .06 | -.05 | -.06 |
| G | -.12 | -.11 | -.06 | -.34 | -.34 | -.12 | -.63 | -.58 | .12 | .14 |
| E | -.21 | -.13 | .22 | .19 | .02 | -.06 | -.70 | -.51 | .03 | -.01 |
| dnm | - | 0 | - | - | - | -.22 | -.48 | -.09 | -.23 | -.39 |
| $C/C_o$ to: |  |  |  |  |  |  |  |  |  |  |
| Q | - | .76 | -.30 | -.25 | -.37 | -.58 | -.02 | .15 | -.02 | -.29 |
| $C_o$ | -.35 | -.43 | -.50 | -.82 | -.78 | -.74 | -.10 | -.09 | -.35 | -.28 |
| $C_oQ$ | - | 0 | -.48 | -.77 | 0.75 | -.70 | -.11 | -.03 | -.10 | -.28 |
| R | -.62 | -.25 | -.69 | -.82 | -.78 | -.38 | -.42 | -.37 | -.62 | -.58 |
| G | -.71 | -.01 | .22 | .28 | .20 | .72 | -.18 | .01 | -.01 | -.03 |
| E | -.87 | -.23 | -.37 | -.53 | -.56 | .42 | -.48 | -.23 | -.62 | -.64 |
| dnm | - | -.11 | - | - | - | .03 | -.40 | .09 | -.10 | -.27 |

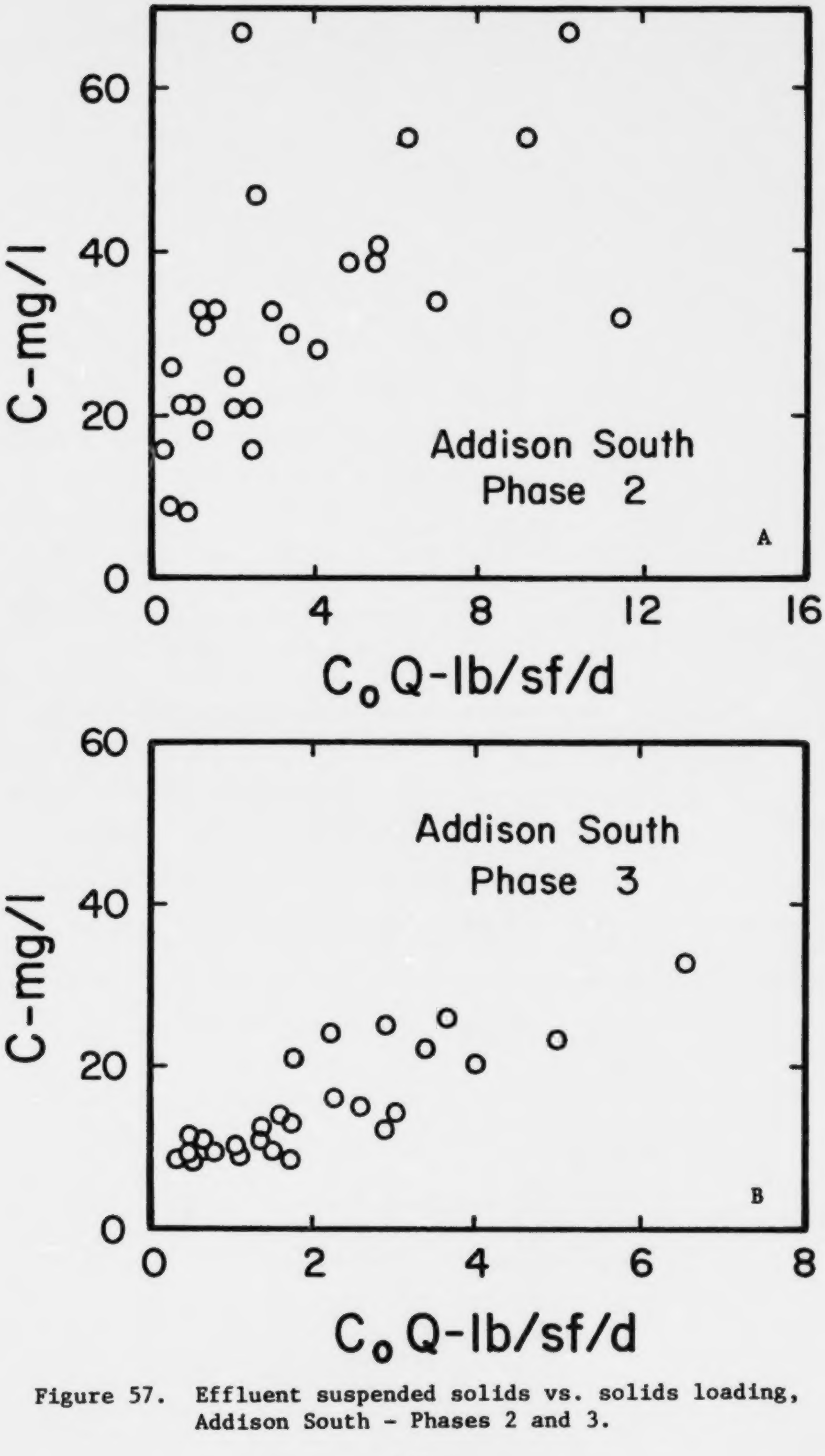


Figure 57. Effluent suspended solids vs. solids loading, Addison South - Phases 2 and 3.

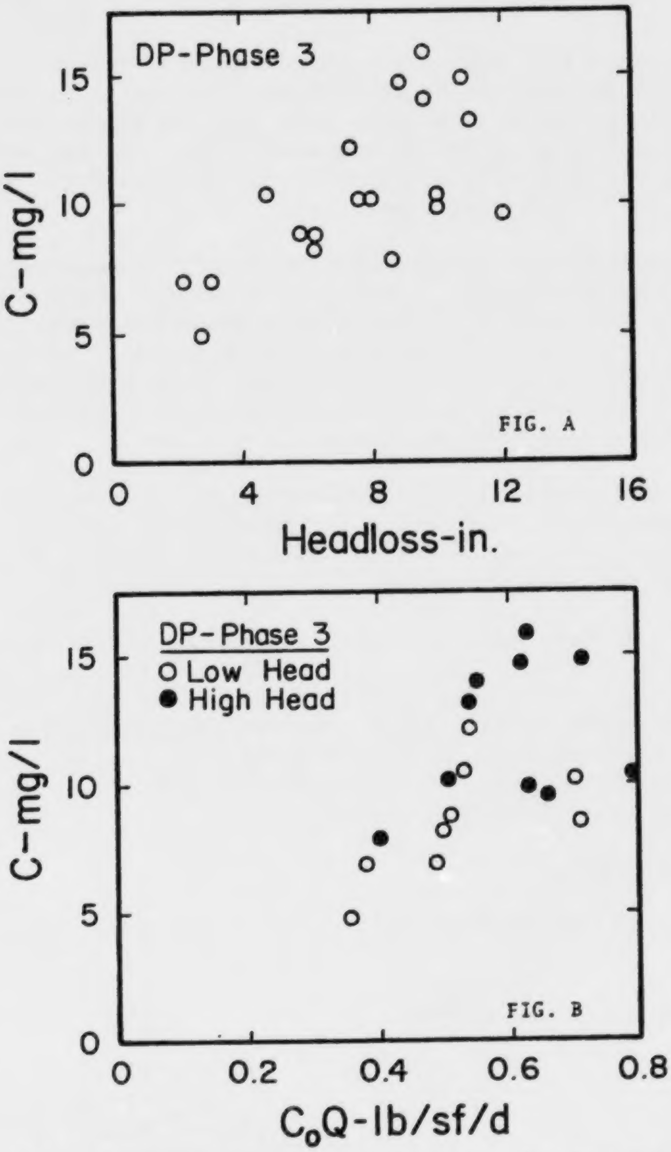


Figure 58. Effluent suspended solids vs. headloss and solids loading, Des Plaines River - Phase 3.

| Figure | Plant |
|---|---|
| 59A | Addison North, Barrington |
| 59B | Des Plaines River, Romeoville |
| 60A | Addison South |
| 60B | Lake Zurich, Lisle, Marionbrook |

The Addison North data show a strong correlation over a narrow range of solids loading. If the data point at high solids loading is excluded for the Barrington data, no trend is apparent. Grab samples at the Des Plaines River plant were obtained during early morning hours when headloss was low (2 to 5 in.). The Des Plaines River data show an opposite correlation for C vs. $C_oQ$, and the Romeoville data show no apparent trend.

The solids loadings for the Des Plaines River and Romeoville plants are much lower than for other plants. The trend shown for the Des Plaines River data may be attributed in part to the smaller particles usually present for low values of $C_o$ which experience deeper penetration of the bed. As solids loading increases, particle size also increases and collection goes through a maximum. At higher solids loading performance is decreased because previously deposited particles are sheared from the bed.

The Addison South data in Figure 60A show wider scatter than for Phase 3. At a solids loadings of 1 lb/sf/day, C is about 5 mg/$\ell$ compared to 10 mg/$\ell$ for Phase 3 suggesting a different particle collection mode, as discussed later. Mean $d_{nm}$ was 12 μm for Phase 4 compared to 8 μm for Phase 3.

Mean $d_{nm}$ for the Lake Zurich, Lisle, and Marionbrook data shown in Figure 60B was 12 μm for each plant. These plants all have tertiary ponds ahead of the filters. At a solids loading of 1 lb/sf/day, C is about 10 mg/$\ell$, the same as for the Addison South Phase 3 data. For the Marionbrook dry weather flow data in Phase 1, C was about 13 mg/$\ell$ at a solids loading of 1 lb/sf/day. These factors strongly suggest that in-depth filtration was the probable particle collection mode for these plants.

## Number Mean Particle Size

Plots of $C/C_o$ vs. number mean particle size are shown in the following figures:

| Figure | Phase | Plant |
|---|---|---|
| 61A | 3 | Addison South |
| 61B | 3 | Des Plaines River |
| 62A | 4 | Addison North, Barrington |
| 62B | 4 | Des Plaines River, Romeoville |
| 63A | 4 | Addison South |
| 63B | 4 | Lake Zurich, Lisle, Marionbrook |

If the data point at 9.5 μm is excluded for Addison South, the plot in Figure 61 generally shows a decrease in $C/C_o$ for larger $d_{nm}$ in a very narrow range as would be expected from theory. For Des Plaines River, the data at

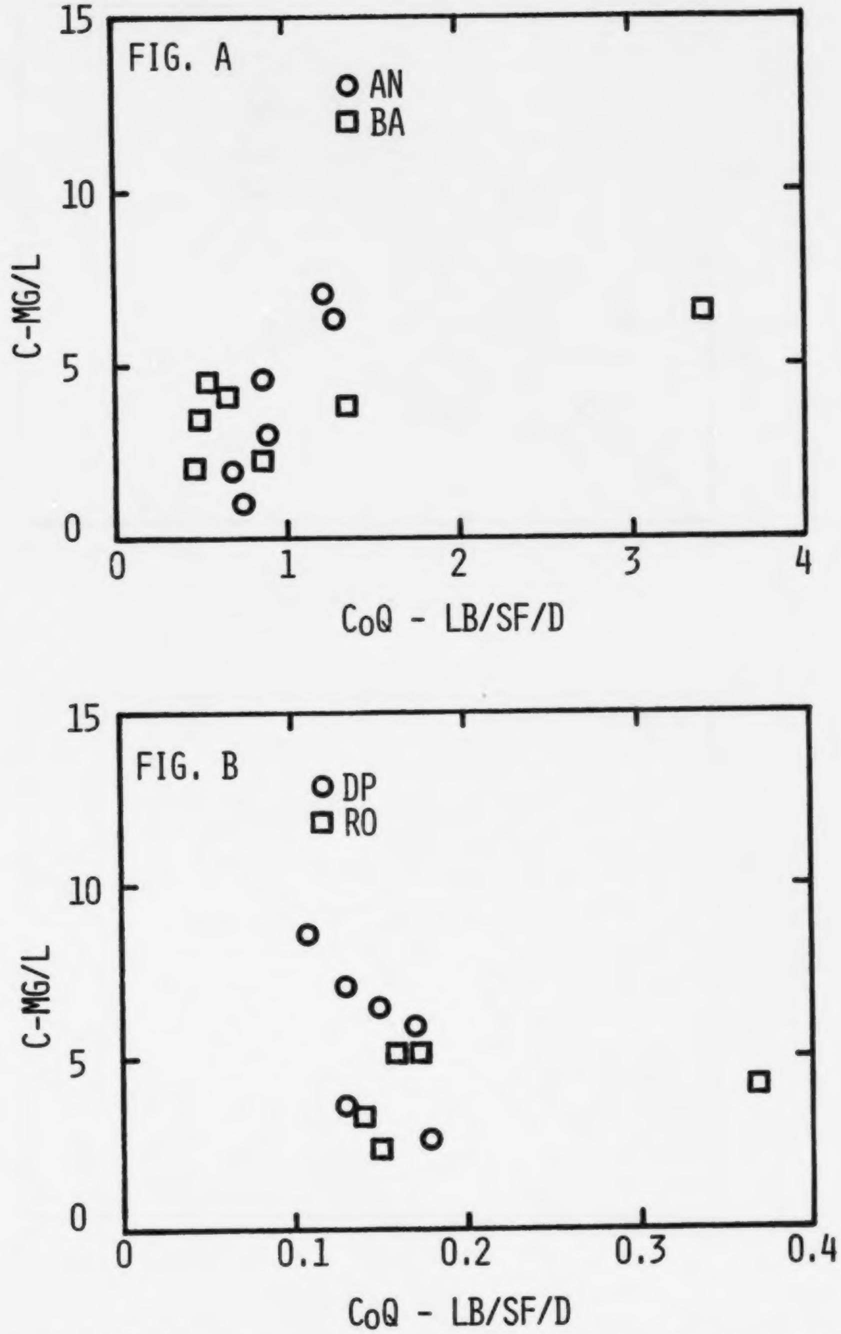


Figure 59. Effluent suspended solids vs. solids loading, Addison North, Barrington, Des Plaines River and Romeoville - Phase 4.

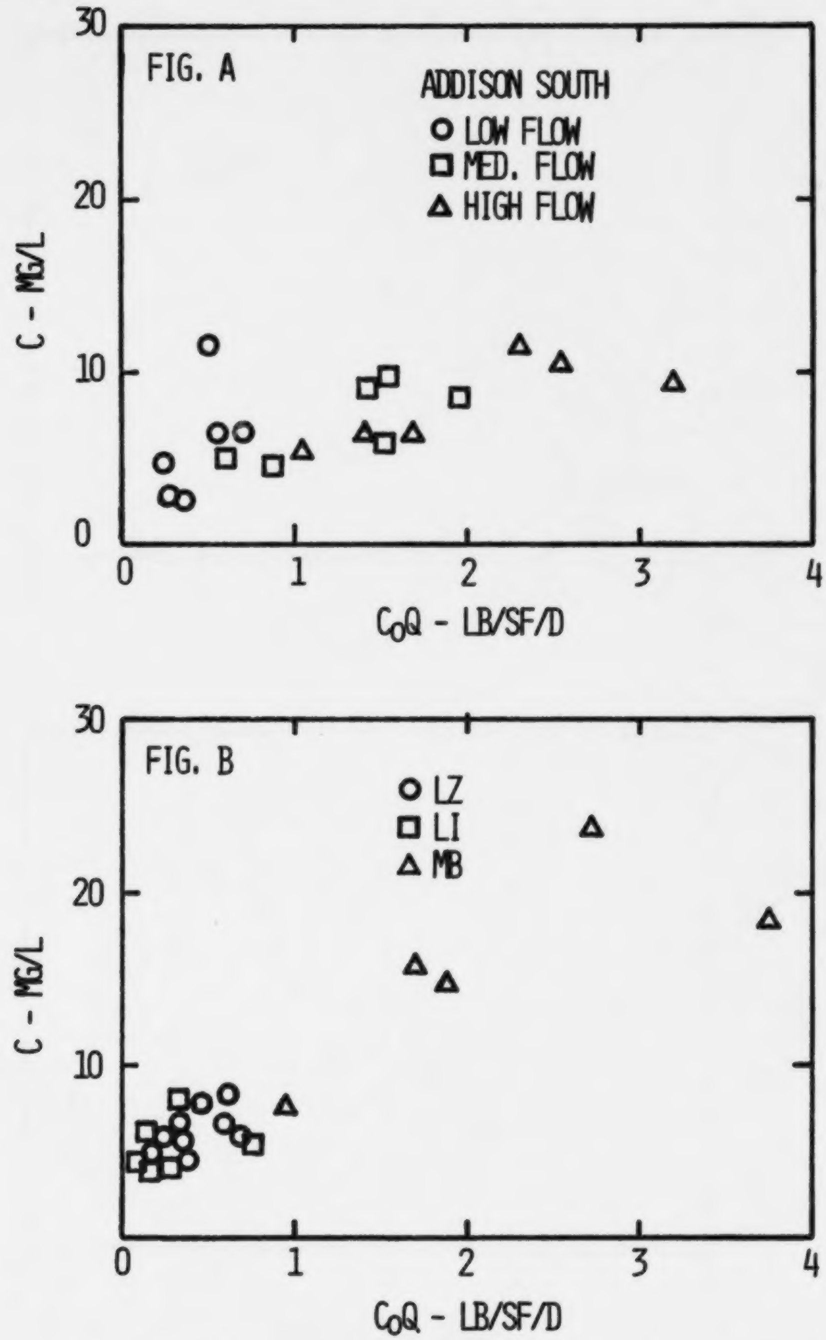


**Figure 60.** Effluent suspended solids vs. solids loading, Addison South, Lake Zurich, Lisle, and Marionbrook - Phase 4.

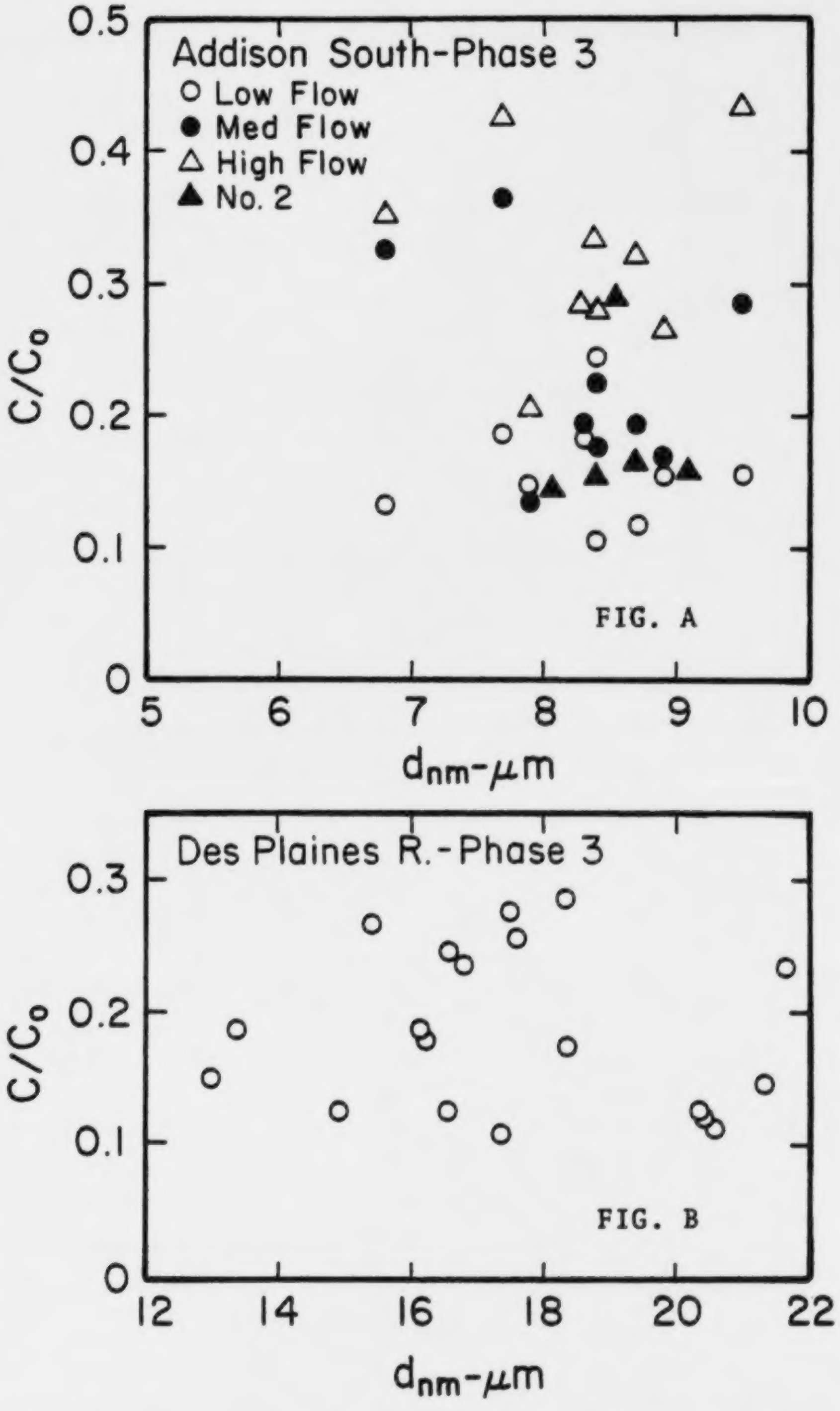


Figure 61. $C/C_o$ vs. particle size, Addison South and Des Plaines River - Phase 3.

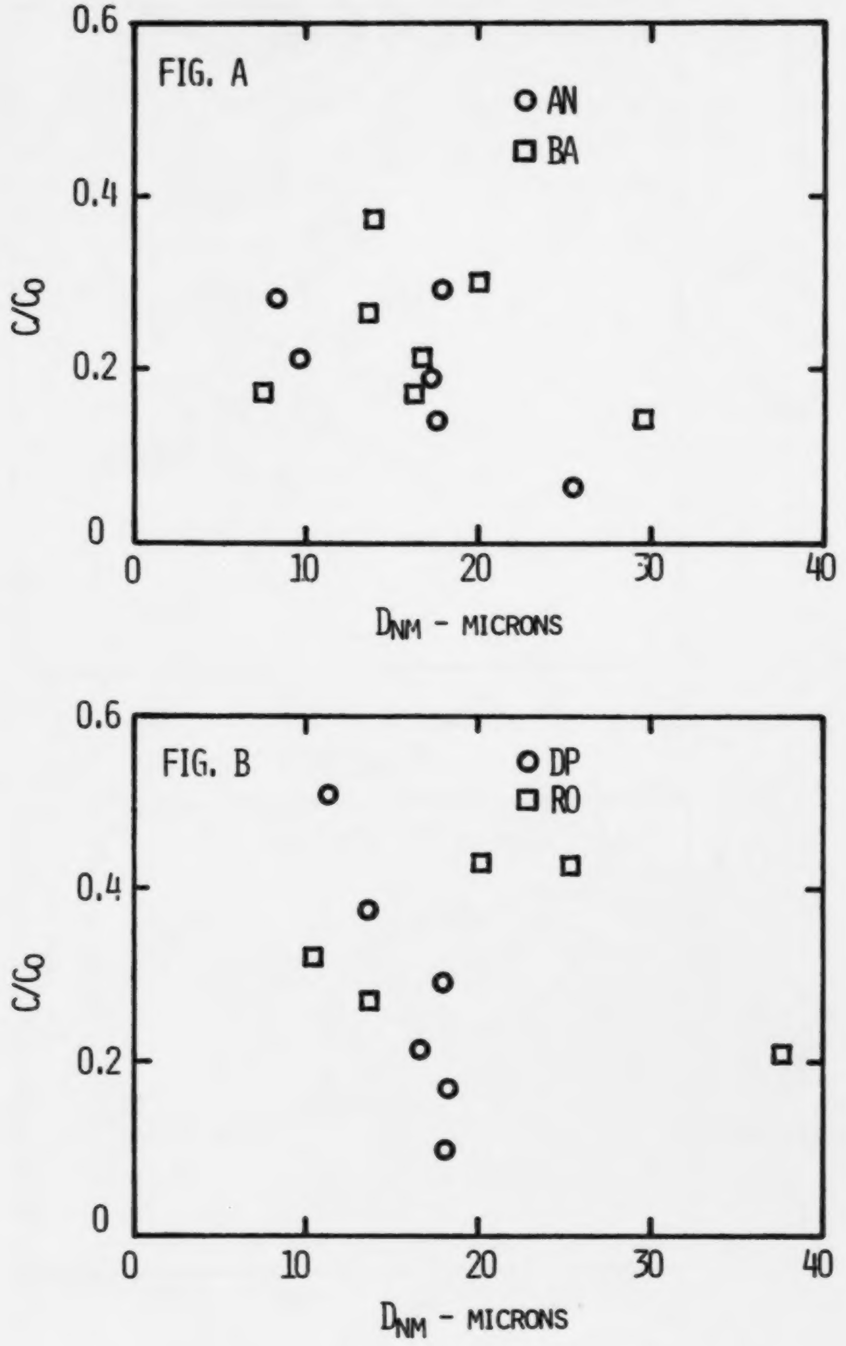


Figure 62. C/C$_o$ vs. particle size, Addison North, Barrington, Des Plaines River, and Romeoville - Phase 4.

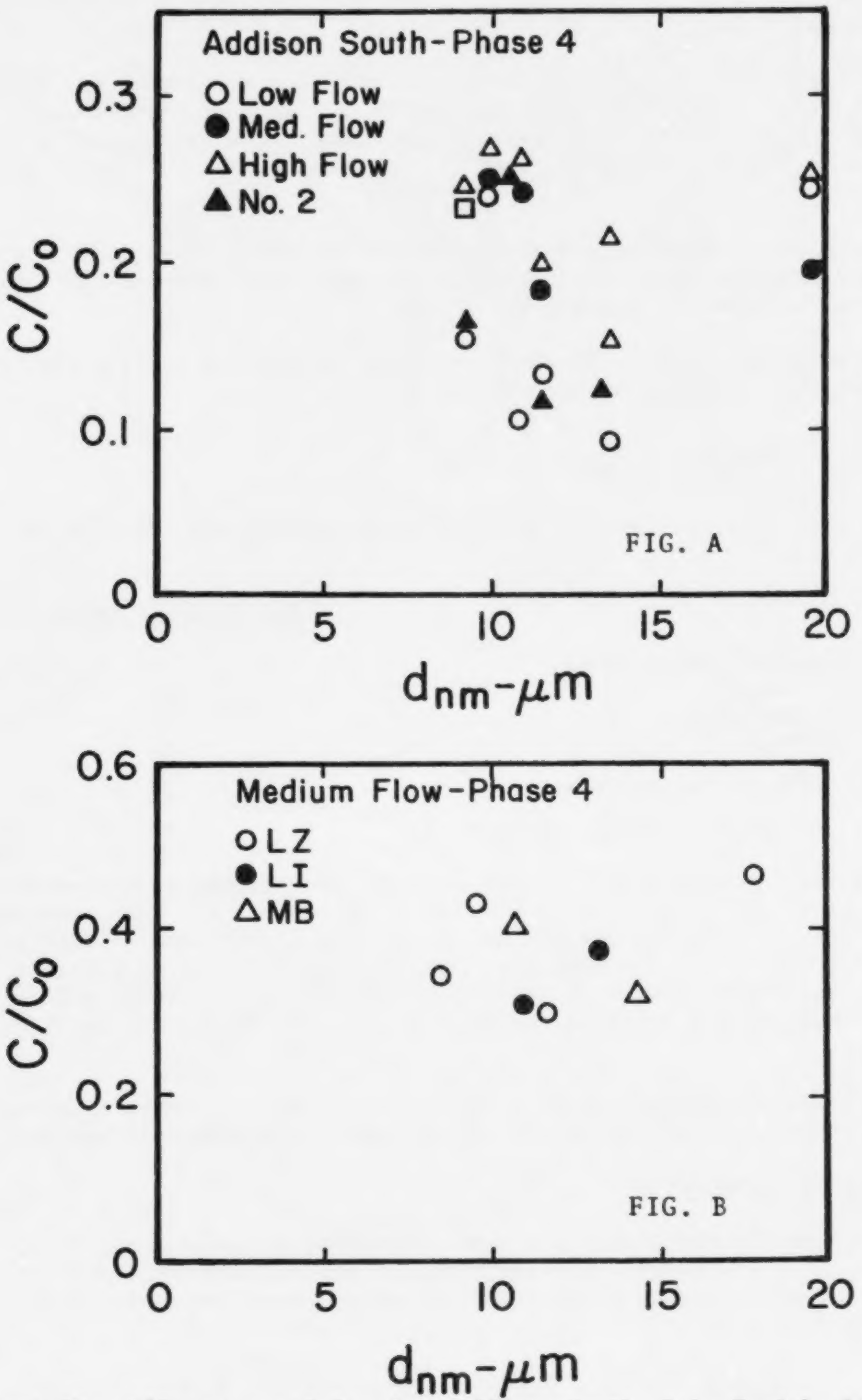


Figure 63. $C/C_o$ vs. particle size, Addison South, Lake Zurich, Lisle and Marionbrook - Phase 4.

high headloss are erratic but the low headloss data show a weak dependence of $C/C_o$ on $d_{nm}$.

In Figure 62 , relatively weak correlations are apparent for Barrington and Romeoville. Except for one data point, a linear decrease in $C/C_o$ for increasing $d_{nm}$ appears to occur for Addison North. The Des Plaines River data show the strongest correlation over the relatively narrow range of $d_{nm}$ of 12 to 18 µm.

The Addison South data shown in Figure 63 show a strong correlation except for the data point at 20 µm. Insufficient data were obtained for Lake Zurich, Lisle, and Marionbrook to show any trends.

In order to compare results with those reported in the literature, data were analyzed to determine constants for:

$$\text{Log}\,\frac{C}{C_o} = a\,d_{nm}^{b}\,, \tag{23}$$

for the data sets that showed the strongest correlation. Results are shown below.

| | b | Significance Level |
|---|---|---|
| Addison South Plant | | |
| Low Q | 0.9 | .20 |
| Medium Q | 0.8 | .05 |
| High Q | 0.4 | .23 |
| Addison North, Phase 4 | 0.5 | .12 |
| Des Plaines River, Phase 4 | 2.0 | .02 |

The significance level, or the probability that the result occurred by chance, varies from 0.02 to 0.23 for the above exponents. The power function coefficient of 2 for the Des Plaines River data is the same as that reported by FitzPatrick (1972) for classical interception and gravity theories. He found by experiment about a 1.5 power dependence for particles smaller than 10 µm. When gravity settling was significant, the dependence increased to the 2nd power.

Although the significance is not high, the Addison South data, where the data point at 20 µm was excluded, show a weaker dependence at higher flow rate,

## Refiltration Parameters

Since both R and E increase with increasing particle size, and $C/C_o$ decreases with increasing particle size, it would be expected that $C/C_o$ would decrease with increasing R and E. Plots of $C/C_o$(log) vs. R are shown in the following figures:

| Figure | Phase | Plant |
|---|---|---|
| 64A | 2 | Addison South #2, Hsiung's data |

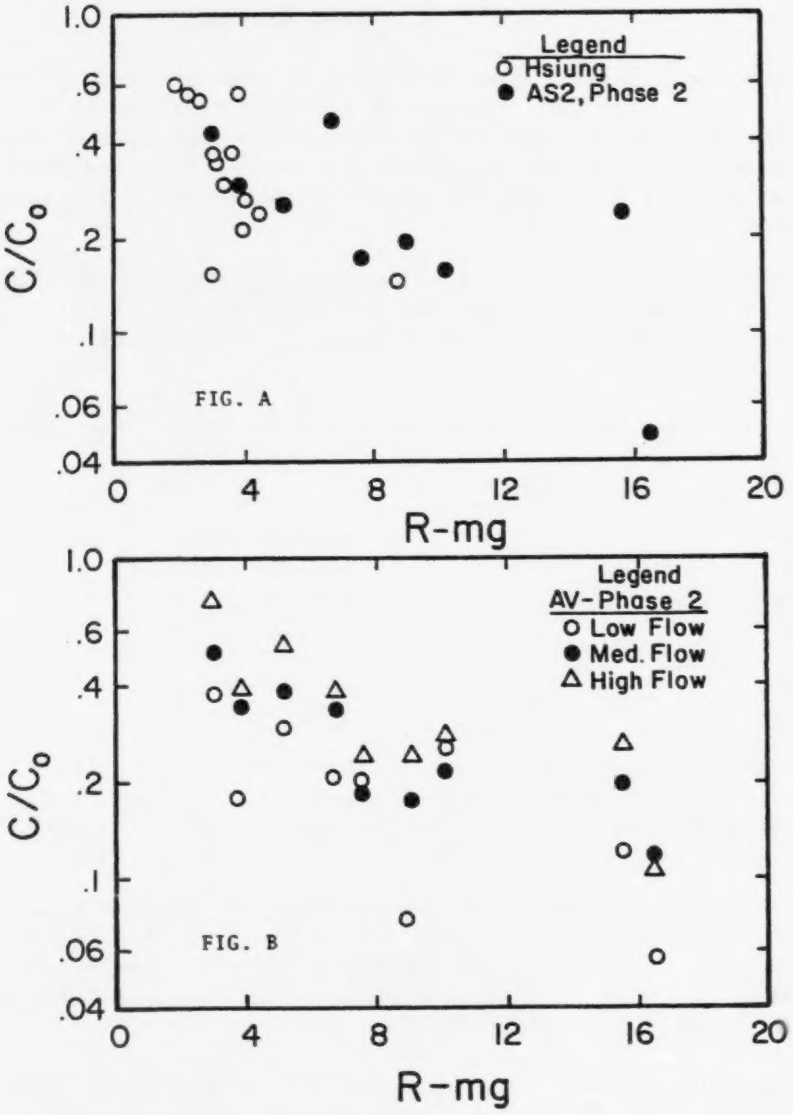


Figure 64. $C/C_o$ (log) vs. R, Hsiung's data, Addison South - Phase 2.

| | | |
|---|---|---|
| 64B | 2 | Addison South, variable flow |
| 65A | 3 | Addison South |
| 65B | 3 | Des Plaines River |
| 66A | 4 | Addison North |
| 66B | 4 | Barrington, Des Plaines River, Romeoville |
| 67 | 4 | Addison South |

The Addison South Phase 2 data in Figure 64 show a higher correlation with R than Hsiung's data, with $C/C_o$ decreasing for larger values of R, as would be expected. Wider scatter is apparent in Figure 65 for the Addison South Phase 3 data, where in-depth filtration apparently dominates, as compared to Phase 2. The Phase 3 Des Plaines River data show wide scatter with a decrease in performance for higher headloss.

The Phase 4 Addison North and Barrington data in Figure 66 show a strong correlation with R. Weaker dependencies are apparent for Des Plaines River and Romeoville. The Addison South data in Figure 67 generally show a weak dependence.

The plots of $C/C_o$ (log) vs. E are shown in the following figures:

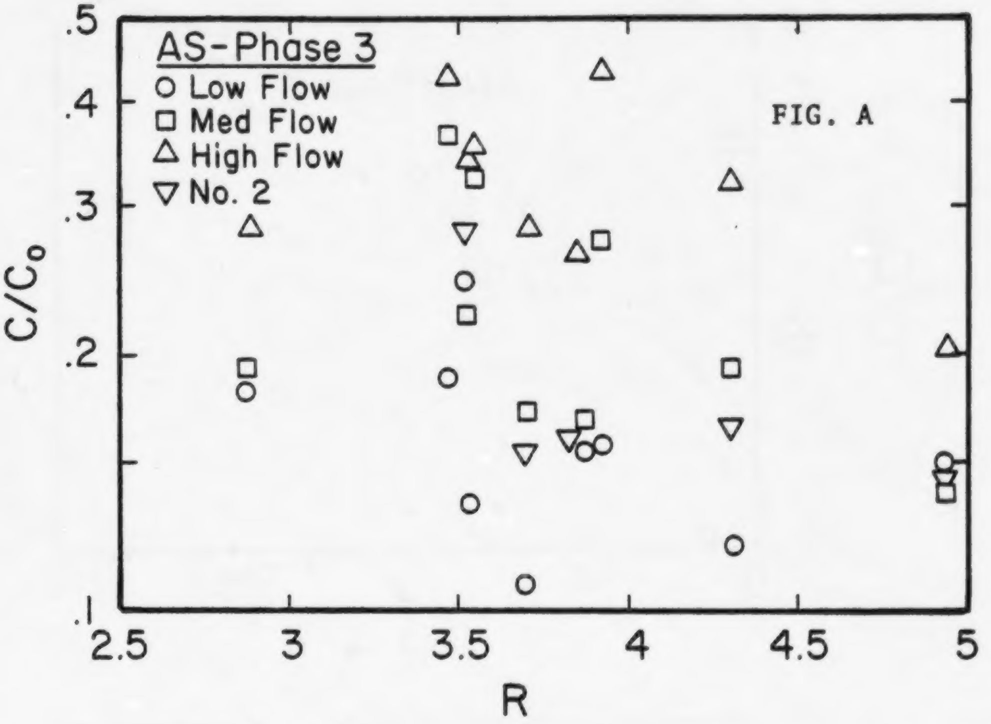
| Figure | Phase | Plant |
|---|---|---|
| 68A | 2 | Addison South #2, Hsiung's data |
| 68B | 2 | Addison South |
| 69A | 3 | Addison South |
| 69B | 3 | Des Plaines River |
| 70A | 4 | Addison North, Barrington |
| 70B | 4 | Des Plaines River, Romeoville |
| 71 | 4 | Addison South |

Hsiung's data in Figure 68 show a stronger correlation with E than that obtained for R, with $C/C_o$ (log) decreasing for larger values of E. In contrast, the Addison South Phase 2 data show the opposite result. The range of E found by Hsiung was 1.3 - 2.3 as compared to 1.3 - 1.9 for this study.

The Addison South and Des Plaines River data for Phase 3 show weak, if any, dependence on E. A similar result was obtained for $C/C_o$ (log) vs. R. Strong correlations are apparent for the Addison North, Barrington, Des Plaines River, and Romeoville data in Figure 70, suggesting that straining may be the dominant particle collection mode for these data.

No apparent relationship is present for the Addison South Phase 4 low flow data in Figure 71. These data cover a very narrow range of E from 1.7 - 1.8. The medium and high flow data do, however, show a decrease in $C/C_o$ (log) vs. E over this narrow range.

In order to test the data sets for the relationship between R and G, regressions were made using an equation of the form $C = f\ (C_o, Q, R, G)$. For one series of tests, the regression coefficient for Q was fixed at 0.26. Results are shown in Table 26 . The ratio of the exponents used by Hsiung (1972)



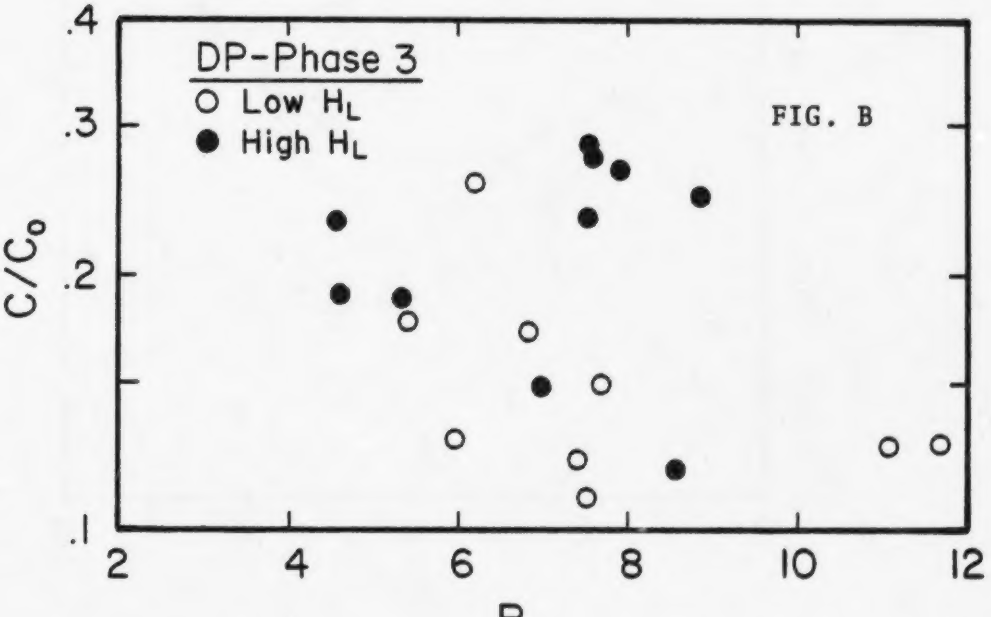


Figure 65. $C/C_o$ (log) vs. R, Addison South and Des Plaines River - Phase 3.

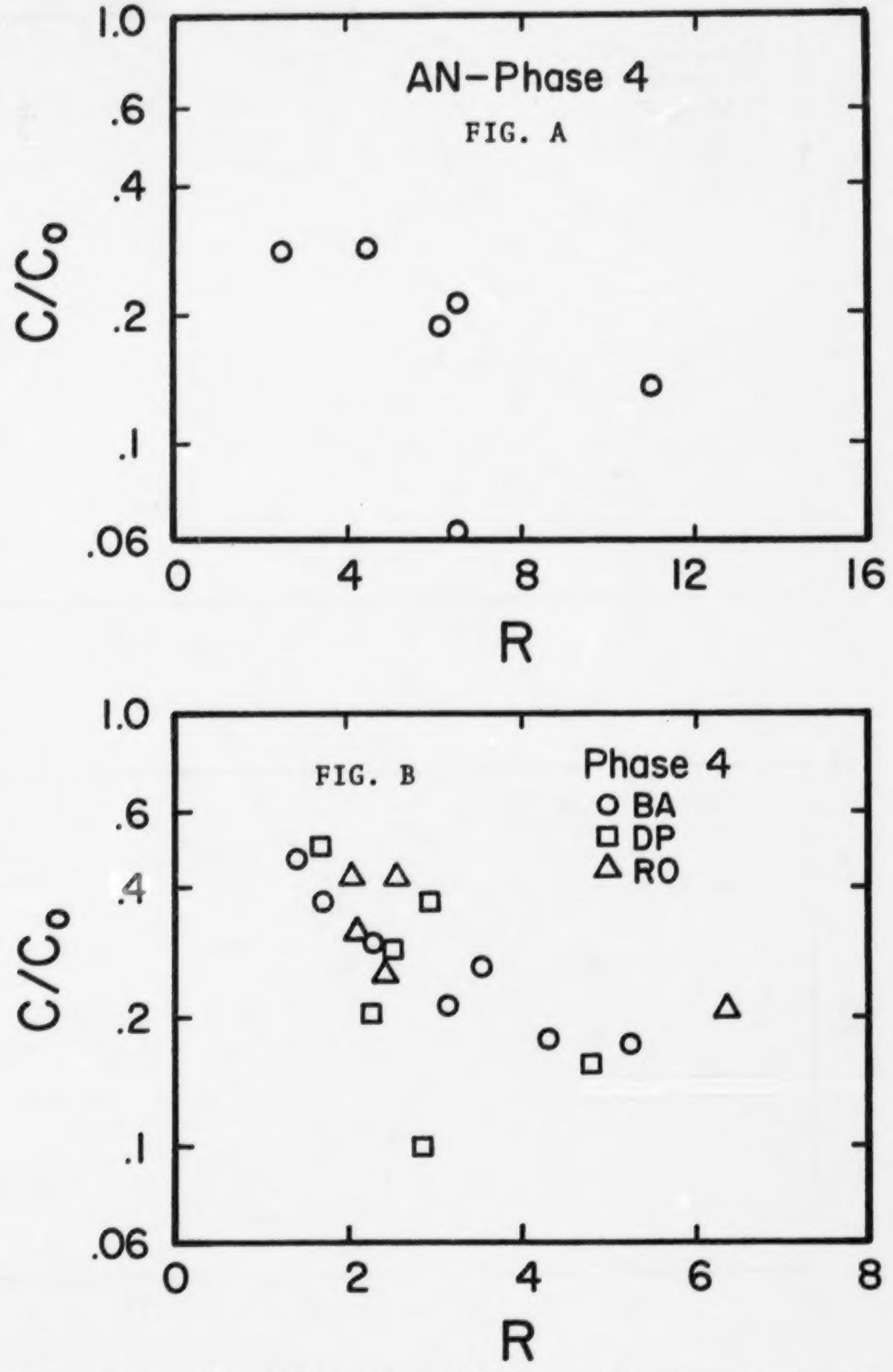


Figure 66. $C/C_o$ (log) vs. R, Addison North, Barrington, Des Plaines River, and Romeoville – Phase 4.

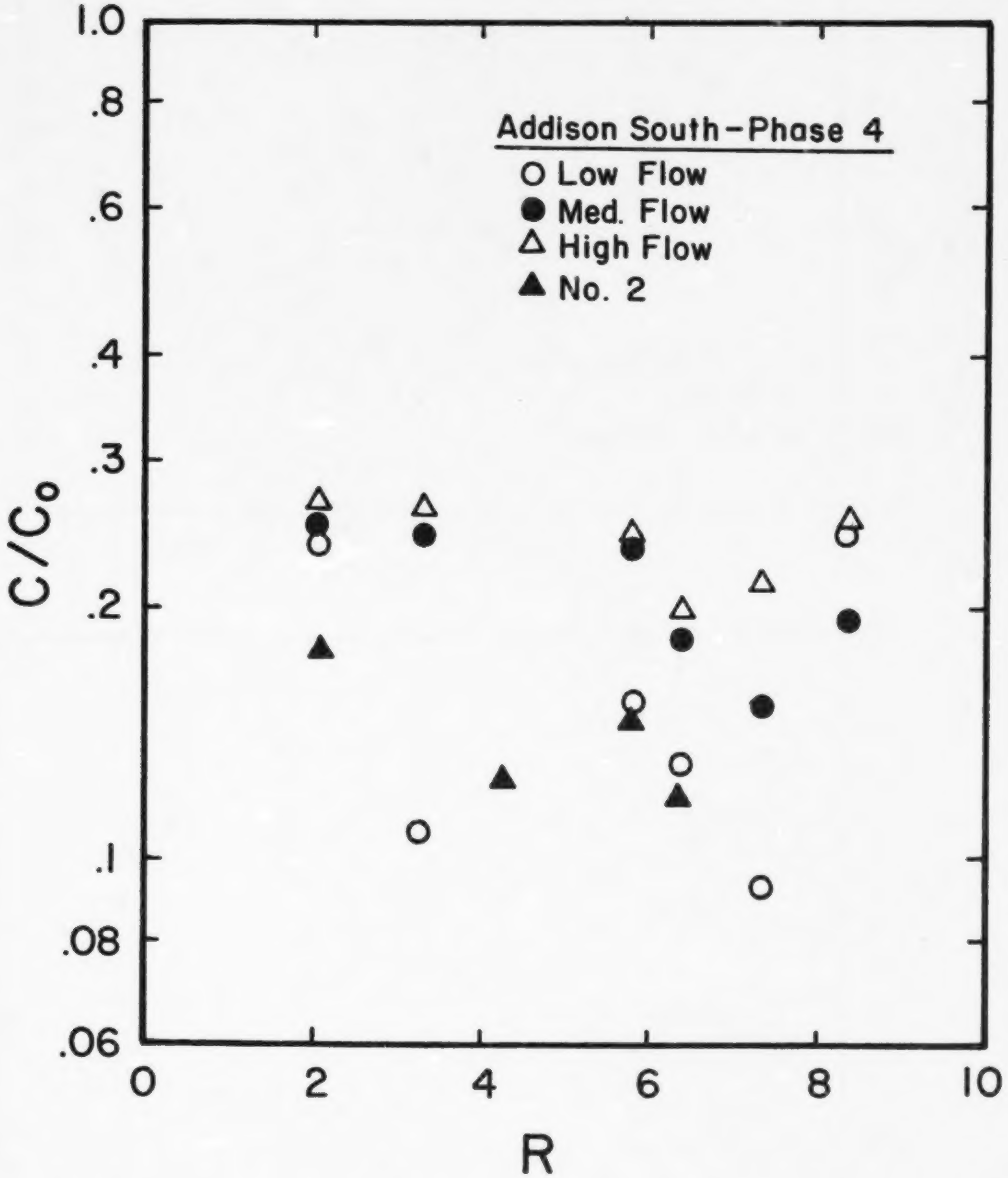


Figure 67. $C/C_o$ (log) vs. R, Addison South - Phase 4.

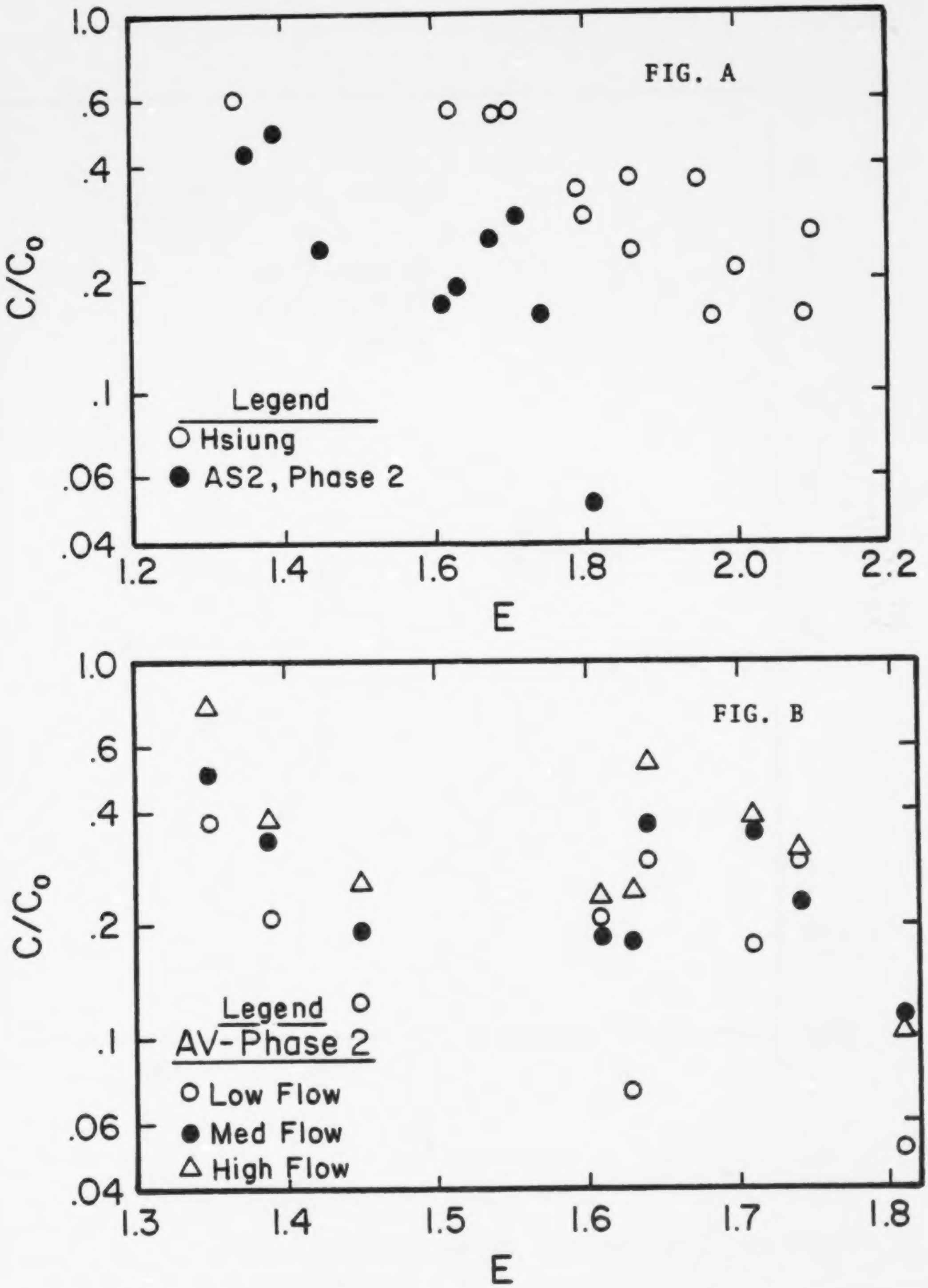


Figure 68. C/C$_o$ (log) vs. E, Hsiung's data, Addison South - Phase 2.

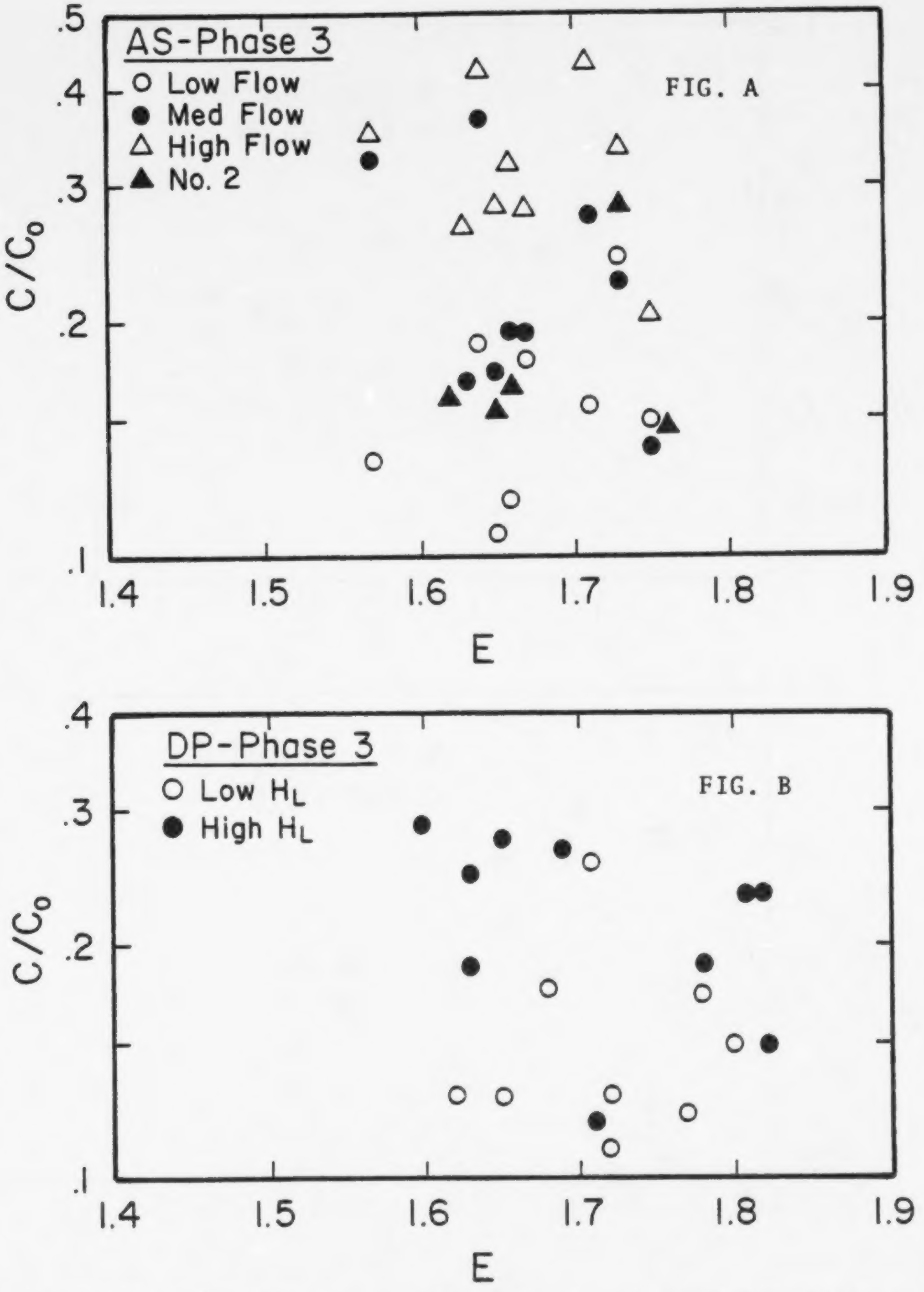


Figure 69. $C/C_o$ (log) vs. E, Addison South and Des Plaines River - Phase 3.

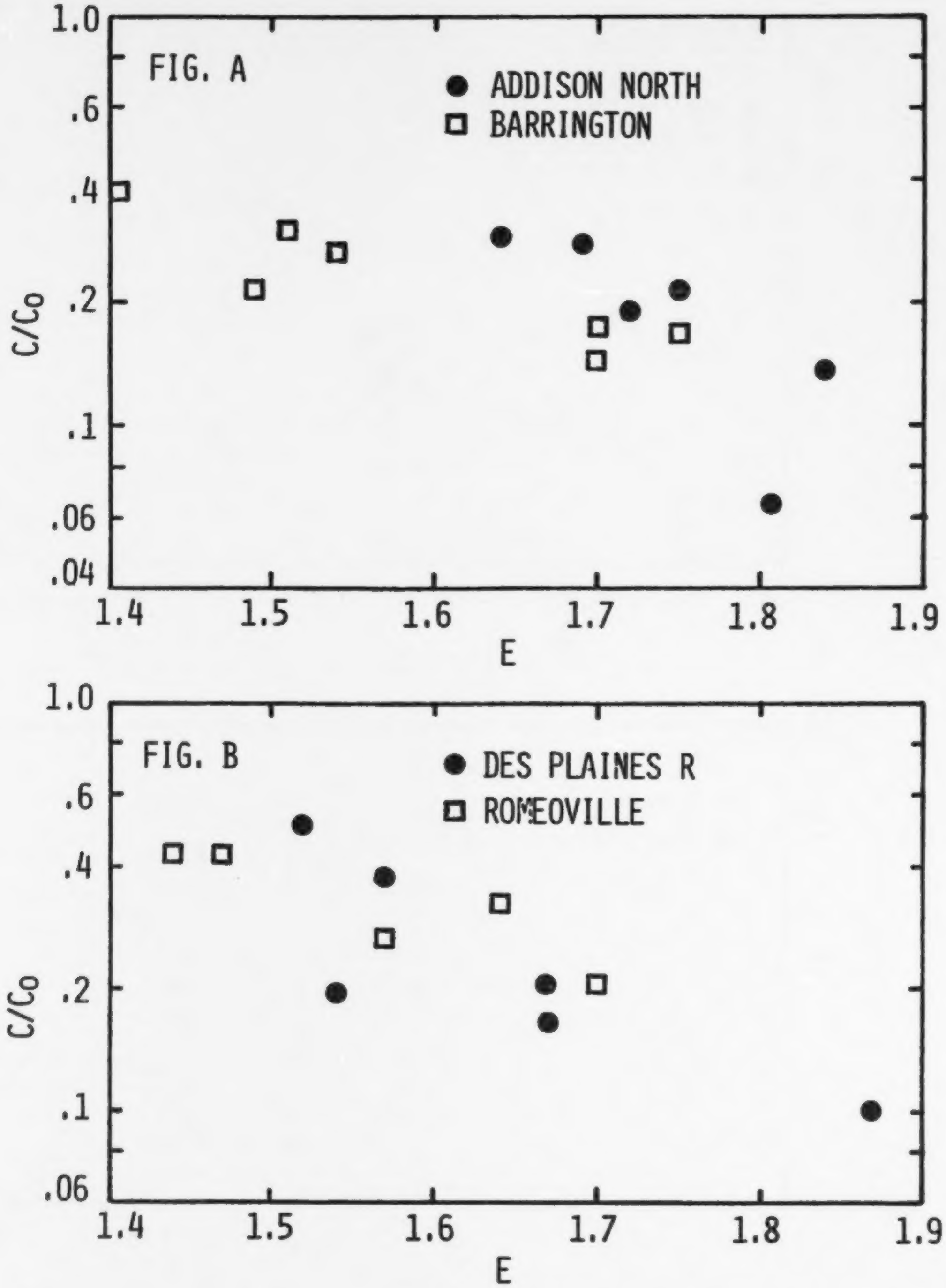


Figure 70. $C/C_o$ (log) vs. E, Addison North, Barrington, Des Plaines River, and Romeoville - Phase 4.

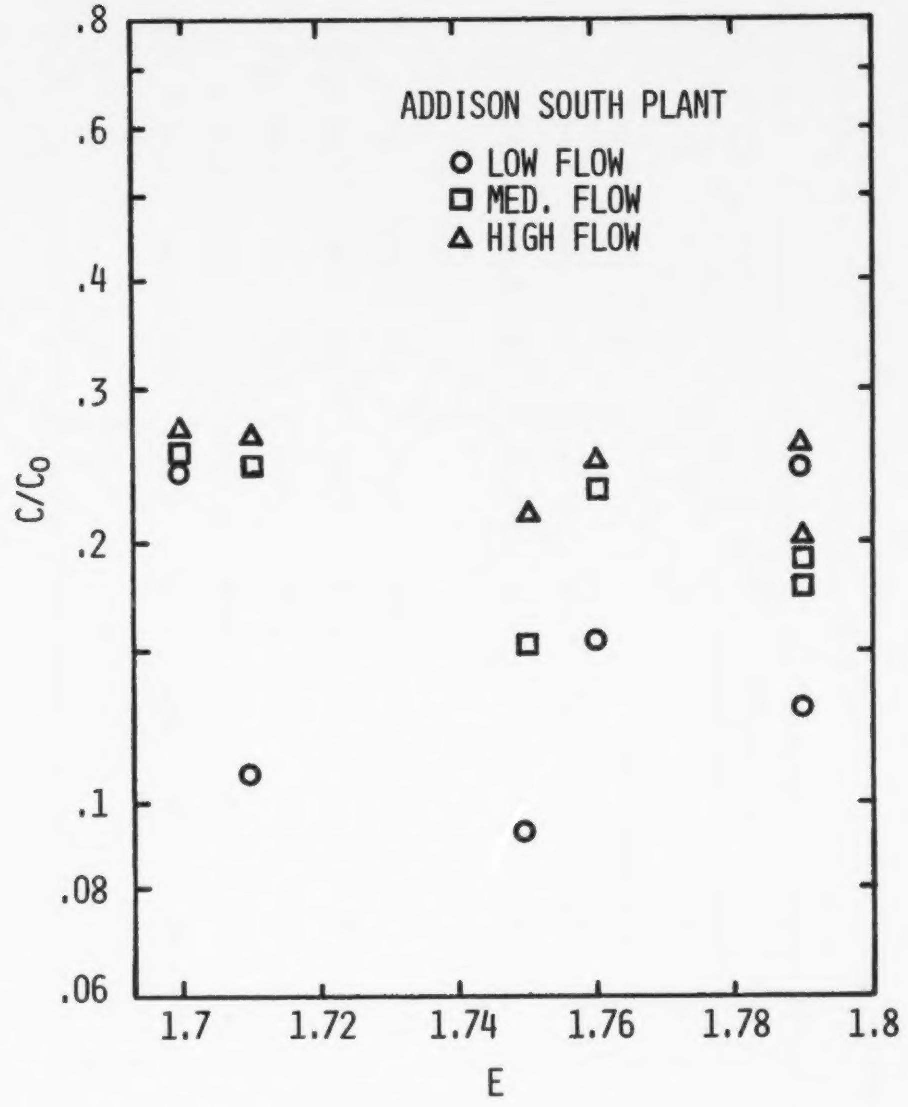


Figure 71. $C/C_0$ (log) vs. E, Addison South - Phase 4.

Table 26. Regression coefficients for $C = aC_o^bQ^cR^dG^e$ and $C = aC_o^bQ^{.26}R^dG^e$.

|  | $C = a\,C_o^bQ^cR^dG^e$ |  |  |  |  |  | $C = aC_o^bQ^{.26}R^dG^e$ |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|
|  | $r_t$ | a | b | c | d | e | $r_t$ | a | b | d | e |
| Hsiung's Data |  | (constant flow) |  |  |  |  | .89 | .52 | 1.37 | -.94 | -1.69 |
| AV- Phase 2 | .85 | .32 | 1.67 | .40 | -.85 | -1.72 | .77 | .34 | 1.66 | -.88 | -1.71 |
| AV- Phase 3 | .84 | 7.39 | .46 | .46 | -.77 | -1.05 | .56 | 4.98 | .56 | -.72 | - .95 |
| Phase 4 |  |  |  |  |  |  |  |  |  |  |  |
| AV | .85 | .032 | 1.26 | .25 | -.006 | 1.22 | .81 | .031 | 1.25 | .010 | 1.27 |
| AN, DP, RO | .89 | 3.50 | 1.23 | .14 | -1.29 | -3.11 | .92 | 3.40 | 1.32 | -1.43 | -3.23 |
| BA, LZ, LI, MB | .87 | .75 | 1.02 | .13 | -.76 | -.73 | .85 | .87 | 1.01 | -.86 | -1.05 |
| MED. Q | .89 | .77 | 1.18 | -.012 | -.76 | -1.35 | .85 | .73 | 1.16 | -.88 | -1.24 |
| ALL DATA | .82 | .84 | 1.08 | .095 | -.73 | -1.22 | .80 | .86 | 1.06 | -.77 | -1.27 |

for R and G in developing the parameter E was d/e = 1/3. The ratios for d/e for the data in Table 26 for the exponent for $Q$ fixed at 0.26 are 0.56 for Hsiung's data, 0.51 for Addison South Phase 2, and 0.44 for the AN, DP, RO data. Higher ratios of 0.76 and 0.82 were obtained for the Addison South Phase 3 and the BA, LZ, LI, MB data sets, respectively. The inconsistent data for Addison South Phase 4 are probably caused by the strong correlation between $C_o$ and E, as discussed previously. The above ratios of d/e are closer to 1/3 for plants where straining was believed to be the dominant particle collection mode.

## DISCUSSION

The physical meaning of the refiltration parameters R and E is somewhat obscure when applied to secondary effluent because of the wide variations of particle size and surface chemistry. Clearly the septum used for the refiltration test does not directly simulate particle removal in a granular bed filter. However, there are some similarities.

Small particles below the size counted plugging the 0.45 μm openings of the Millipore filter paper would reduce both R and E. The same particles will be only poorly removed in a granular filter. Thus low values of R and E may then correlate with high values of C and $C/C_o$.

Treeweek and Morgan (1977b) found that the refiltration test was the best measure of the effectiveness of cationic polymers in flocculating an *E. coli* suspension. The refiltration test simulates to some extent the packing of several particles in the crevices in the filter medium. Since it is a measure of the extent of agglomeration of particles, a good correlation with removal efficiency might be expected because particle-particle interactions are probably more important than particle-media interactions for filtration of secondary effluents.

Refiltration parameters may also be a measure of particle shape. Rough shaped particles would tend to increase the fluid drag and the refiltration time. However, suspended particles in this study appeared to have the same general shape.

Clearly the refiltration test lumps together a number of suspension properties. This study has shown that there is no relationship betwen $C_o$ and refiltration parameters except where high $C_o$ is an indication of carryover of large floc particles from final clarifiers or the $C_o$ range is large. Weak correletions of refiltration parameters and particle size characteristics were obtained for nearly all data. It is highly likely that particle sizes smaller than the range counted may have an effect on the refiltration test. Particle size showed a good correlation with filter performance for several individual plant data but did not correlate well between plants. In general, refiltration parameters showed a strong correlation with $C/C_o$ except for plants where in-depth filtration was believed to be the dominant particle collection mode. For most situations, E showed a stronger correlation with performance than R.

# CHAPTER X

## DEVELOPMENT AND TESTING OF OPERATIONAL MATHEMATICAL MODELS--PHASES 2, 3, AND 4

### INTRODUCTION

This chapter tests the hypothesis that filter clarification efficiency can be better characterized by including properties of secondary effluent suspensions in semiempirical models rather than conventional parameters only. Methods used to test hypotheses that straining or in-depth filtration was the dominant particle collection mode for individual runs and for individual plant data are described. Finally, models describing filter clarification efficiency are developed and tested using independent data sets.

### DETERMINATION OF FILTRATION MODE

Since a preliminary cut of the data between straining and depth filtration is necessary, more refined attempts to segment and correlate the data were necessary. Methods used are described below.

### Relationship Between $d_p/d_m$ and Number Flux of Particles

Kavanaugh's (1974) relationship (Equation 7) for the ratio of particle size to media size ($\bar{d}_p/d_m$) and the number flux ($J_{N_0}$) of particles to the filter bed was tested using Phase 4 data. A reproduction of his plot of $\log_{10}(\bar{d}_p/d_m)$ vs. $\log_{10} J_{N_0}$ (particles $cm^{-2}$ $sec^{-1}$) is shown in Figure 72. For data where unisize suspensions were not used, $\bar{d}_p$ is characterized by number mean particle size and the particle number flux is based on total number of particles.

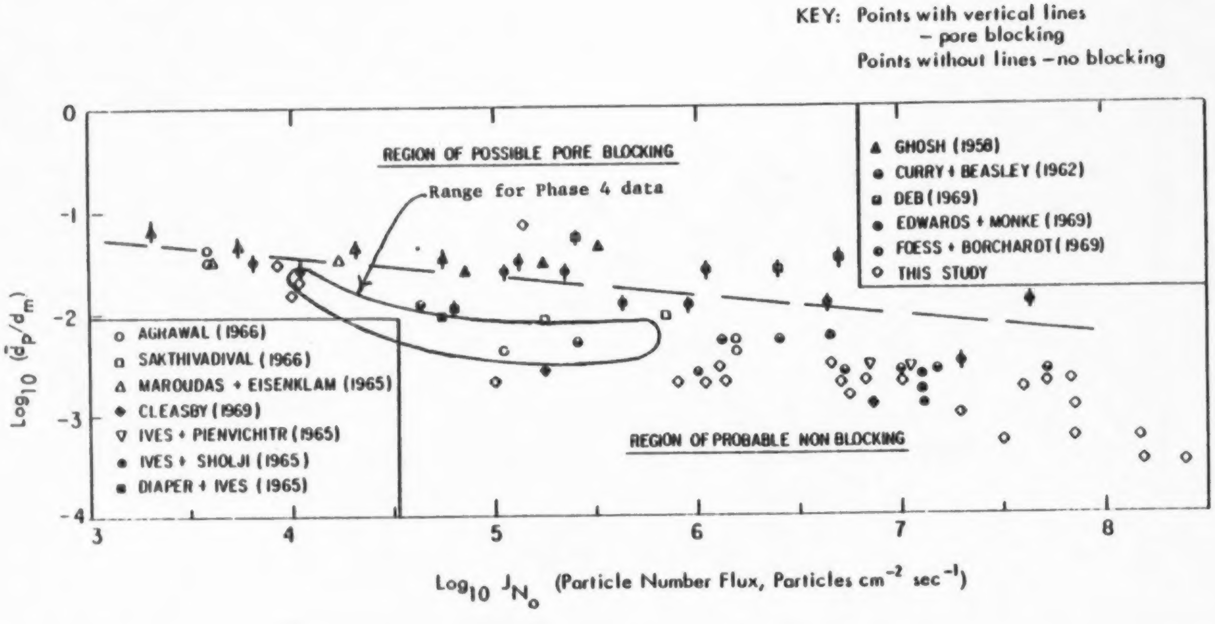
For this analysis, $\bar{d}_p$ was characterized by $d_{nm}$ and $d_m$ by the $d_{50}$ of anthracite for dual media filters and the $d_{50}$ of sand for the single medium filters. Particle number flux was calculated using the total number of particles. The range of the data is shown on Kavanaugh's plot and tabulated below.

| | Phase 4 | Kavanaugh |
|---|---|---|
| $\log_{10}(\bar{d}_p/d_m)$ | -1.3 to -2.5 | -1.1 to -3.4 |
| $\log_{10} J_{N_0}$ | 3.9 to 5.8 | 3.3 to 8.4 |

Individual data are shown in Figure 73.

The results are influenced to a large extent by the range of $d_{50}$ of 0.7 to 2.7 mm. Except for Des Plaines River and Romeoville, the ratio of $d_{nm}/d_{50}$

Figure 72. Pore blocking and non-blocking regions in filtration of stabilized solids. (reprinted with permission from Kavanaugh, 1974).



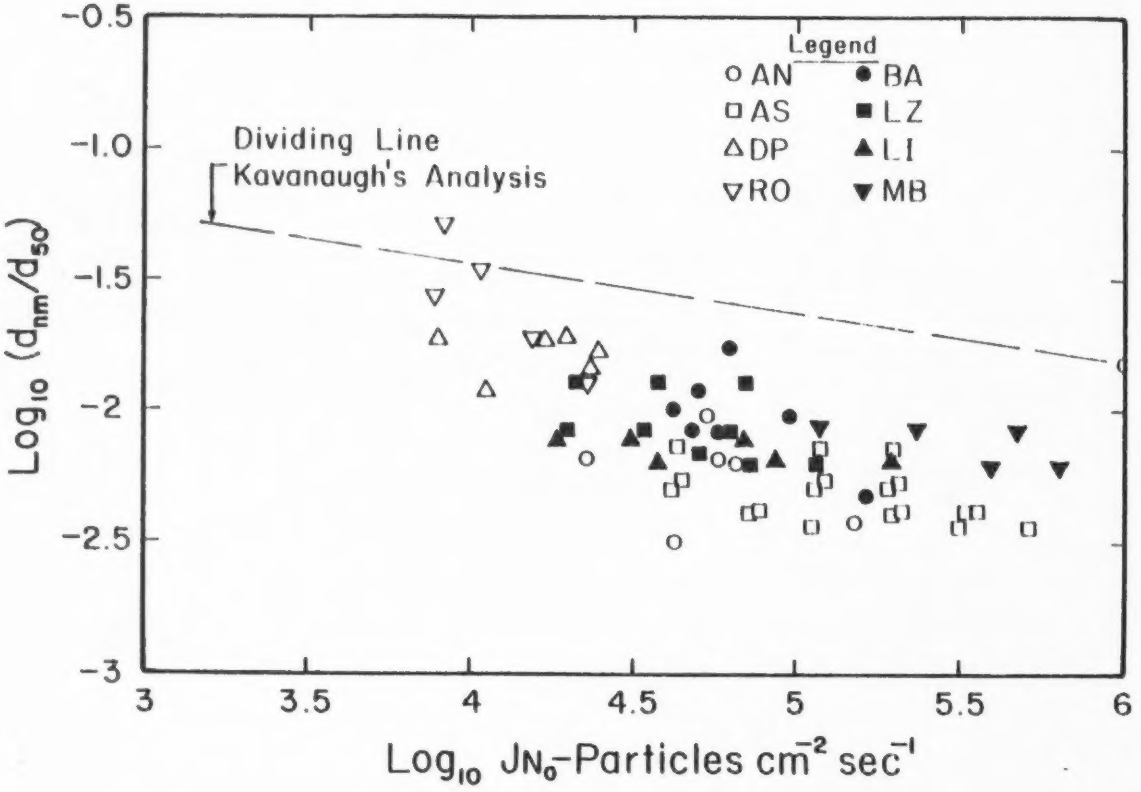


Figure 73. $\text{Log}_{10}$ $(d_{nm}/d_{50})$ vs. $\text{Log}_{10}$ $J_{N_0}$ - Phase 4.

is about an order of magnitude below that proposed by Kavanaugh as the dividing line for possible pore blocking. It is important to note that his data are based on unflocculated suspensions. No attempt was made to segment data on this basis because the data (solid data points in Figure 73), where in-depth filtration was considered to be significant in subsequent analyses, were closest to the proposed dividing line.

Kavanaugh (1974) also did an analysis for the case of straining of destabilized particles, and tested the relationship of filter coefficient or $\mathrm{Log}_{10}$ $C/C_o$ and particle number flux using the values of $C/C_o$ for the top several inches of filter media. He found no apparent relationship and noted that a mat of solids did not form at the filter media surface. A plot of $C/C_o$ (log) vs. Log $J_{N_O}$ for the Phase 4 data is shown in Figure 74. The data in Figure 74 show wide scatter with no apparent trend.

## Testing Data with In-Depth Filtration Model

If straining is the dominant particle collection mode, then a poor fit with in-depth filtration models should result unless the models predict similar dependencies on variables. This hypothesis was tested using the Marionbrook model for dry weather flow (Equation 22). A plot of calculated vs. measured C is shown in Figure 75 for Phase 4 data.

From Figure 75A, calculated C appears to be somewhat independent of measured C. This result is not surprising since straining is expected to be the dominant particle collection mode for the fine-grained sand filters. Although the Addison North and South data appear to follow a linear relationship, the model greatly overpredicts C suggesting that straining is significant.

An excellent fit is apparent for the Lake Zurich, Lisle, and Marionbrook data in Figure 75B, where C is predicted within ± 25 percent for 85 percent of the data, strongly suggesting that in-depth filtration is the mode of particle capture for these situations. The model greatly overpredicts C for the Barrington data, suggesting that straining is significant.

## Evaluation of Data on a Common Basis

A method was necessary to evaluate the data on a common basis. This was done by assuming the following relationship for straining:

$$C/C_o = a\, C_o^b\, Q^c\, E^d\ , \qquad (24)$$

where a, b, c, and d are constants.

Rearrangement of Equation ( 24 ) gives:

$$\frac{C/C_o}{C_o^b\, Q^c} = a\, E^d\ , \qquad (25)$$

and taking logs of both sides yields

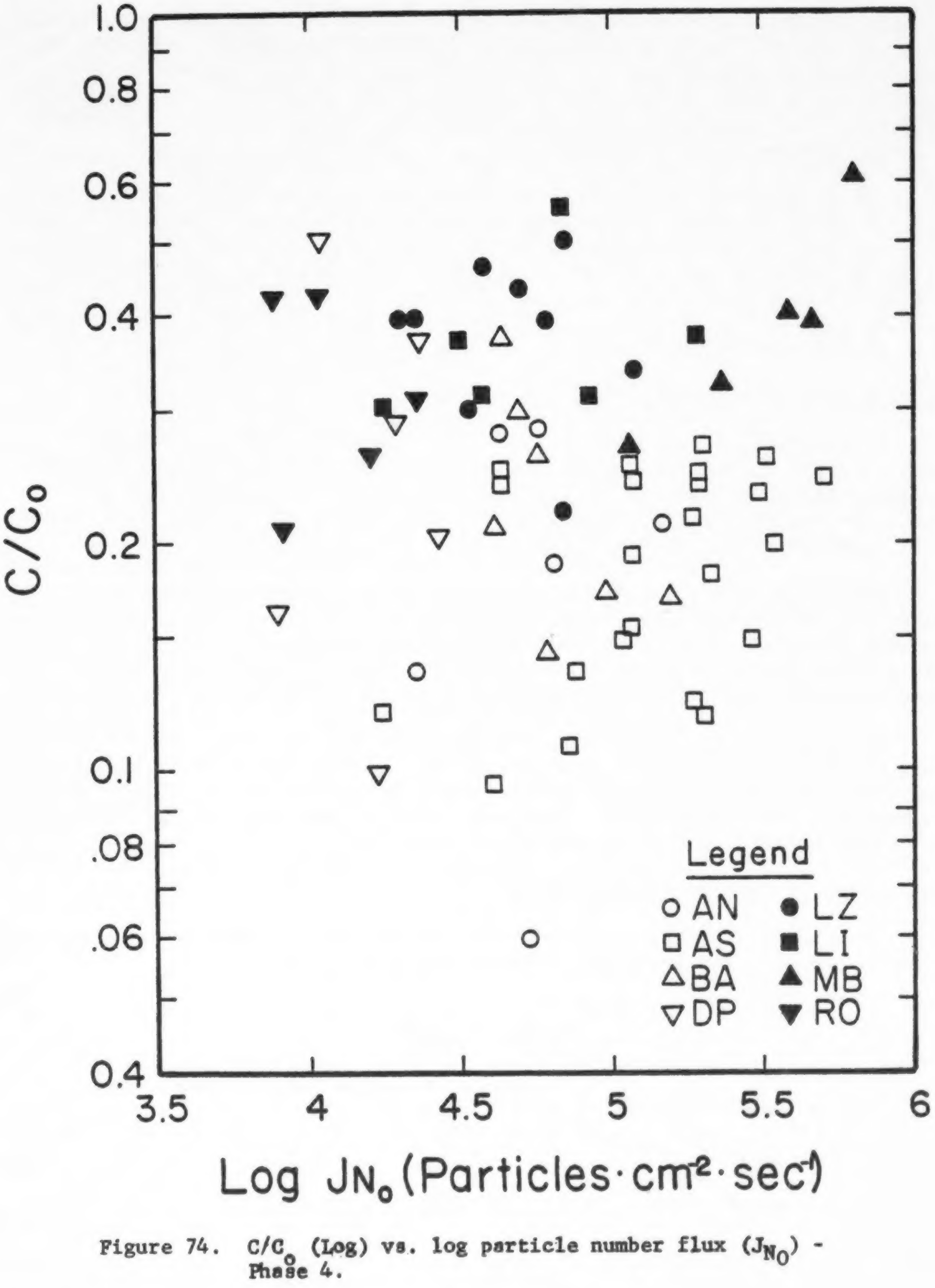


Figure 74. C/C$_o$ (Log) vs. log particle number flux ($J_{N_O}$) - Phase 4.

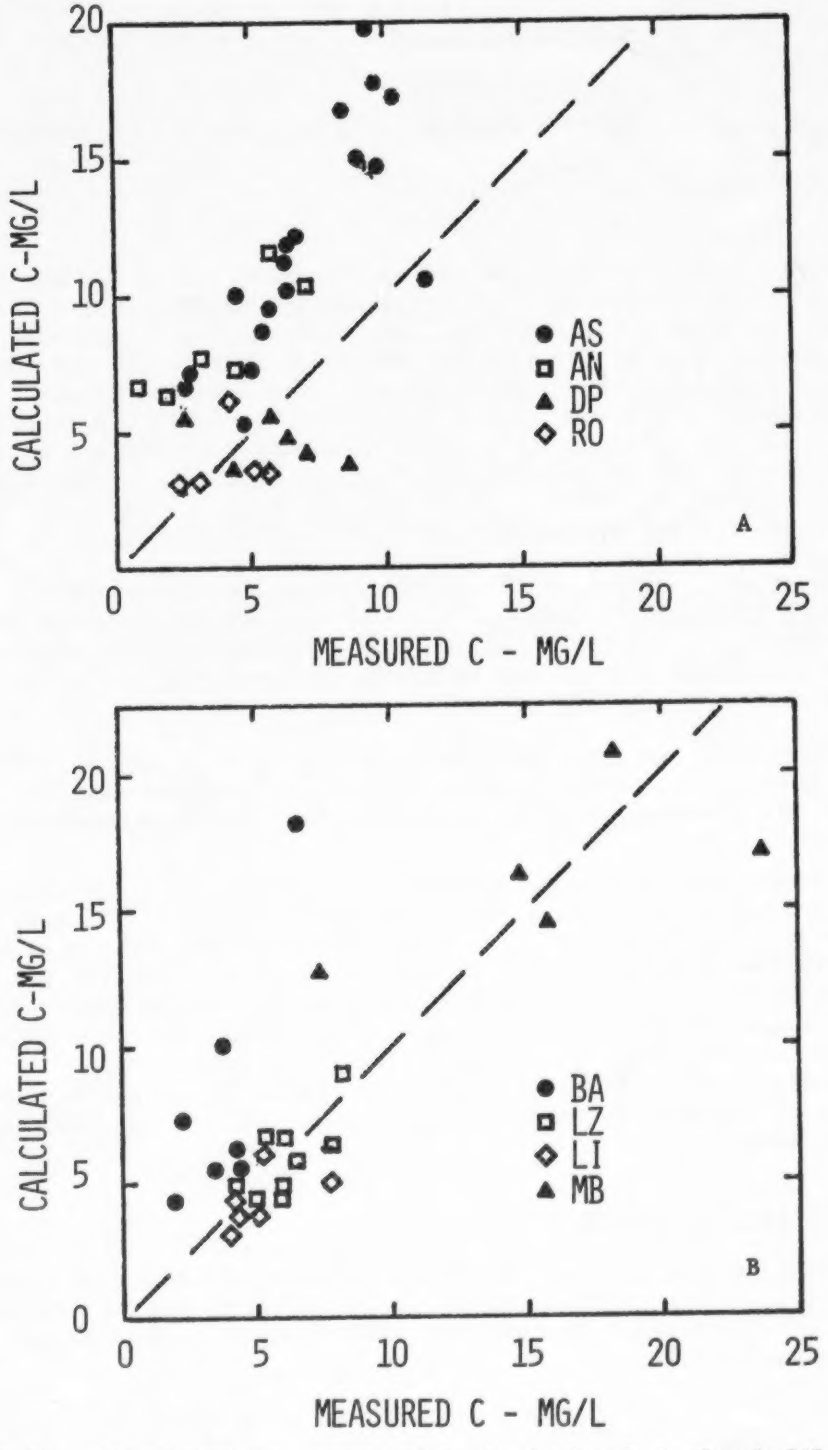


Figure 75. Calculated vs. measured C, Marionbrook in-depth filtration model, (Eqtn. 22) - Phase 4 data.

$$\text{Log}\ \frac{C/C_o}{C_o^b Q^c} = \text{Log a} + \text{b Log E}. \tag{26}$$

Rather than compress the data by plotting E on a log scale, data were "normalized" by plotting Log $\frac{C/C_o}{C_o^b\ Q^c}$ vs. E.

Regression coefficients obtained for Equation ( 24 ) for the Addison South Plant data, where flow to individual filters was varied, were 0.49 for b, 0.26 for c, and -10.6 for E. Regressions were also run for a number of combinations of individual data sets. If flow to individual filters was not varied, the coefficient c varied over a wide range with some negative values. A similar result was obtained for the Phase 1 data. For the Addison North, Des Plaines River, and Romeoville plant data, where straining was believed to be the dominant particle collection mode, regressions were performed using a fixed coefficient at 0.26 for c. The resulting coefficient for b was 0.4. Values of 0.26 for c and 0.4 for b were then used to normalize the data.

Plots of $(C/C_o)/C_o{}^{0.4}\ Q^{0.26}$ vs. E are shown in Figures 76 and 77 for two groupings of the data. Trends for the other groupings are shown as a dashed line on each figure. For the Addison North, Addison South, Des Plaines River, and Romeoville plant data, shown in Figure 76, straining is considered to be the dominant particle collection mode.

In Figure 77, the individual data for Lake Zurich, Lisle, and Marionbrook show the opposite dependence on E. This further suggests that in-depth filtration is the dominant particle collection mode for these plants.

The Barrington data do not correlate well with the in-depth filtration model from Phase 1, but show a strong correlation with E in Figure 77. However, removal efficiency for Barrington is higher than the plants in Figure 77 at equivalent E values. This result cannot be explained on the basis of data obtained in this study. Perhaps in-depth filtration and straining are of nearly equal importance in this case. This postulation may be supported by considering the slope of the trend line for the Barrington data and the plants in Figure 76. The steeper slope in Figure 76 indicates a stronger dependence of performance on E if straining is the apparent dominant particle collection mode.

## Dimensional Straining Group

In order to segment data for better correlation using the straining model (Equation ( 24)) a semi-empirical dimensional grouping to characterize straining was developed. The approach used is shown in Appendix C. The grouping selected was:

$$N_{STR} = \frac{C_o\ Q\ E^6\ d_{nm}^4}{\mu^2\ d_{10}^2} \tag{27}$$

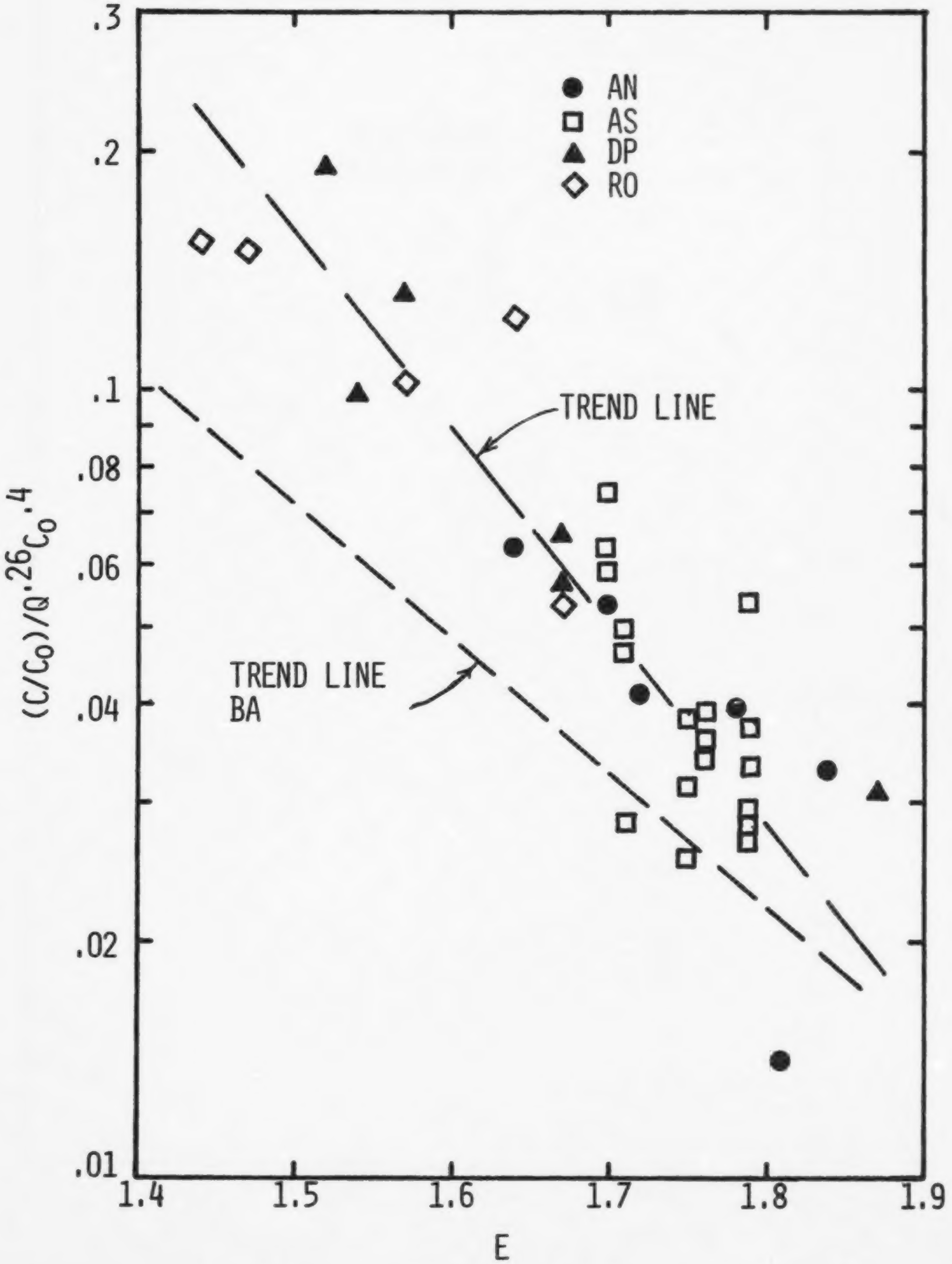


Figure 76. Normalized data plots, Addison North, Addison South, Des Plaines River, and Romeoville.

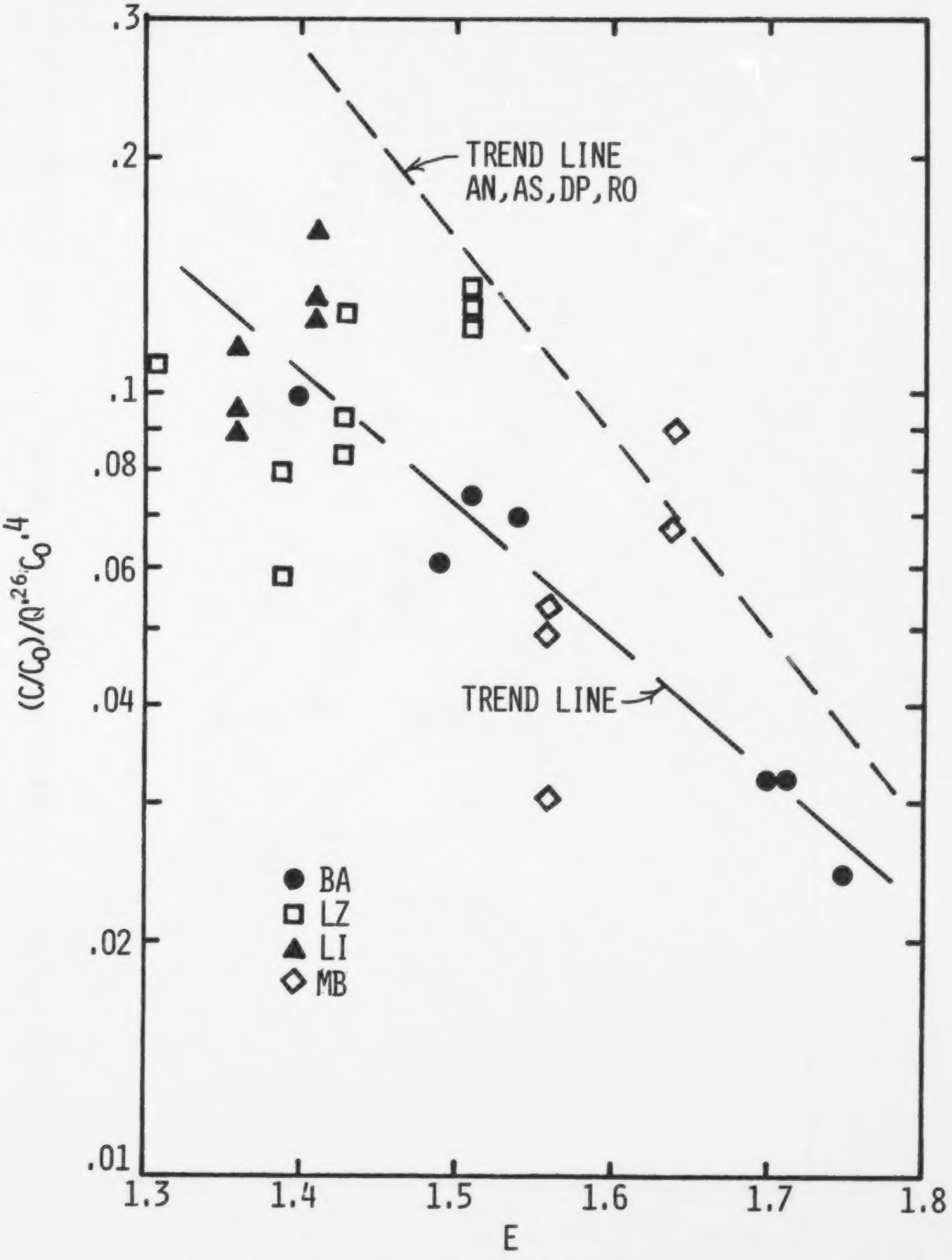


Figure 77. Normalized data plots, Barrington, Lake Zurich, Lisle, and Marionbrook.

The filter medium dimension used was the effective size ($d_{10}$) of the anthracite for dual media filters and sand for single medium filters. Values of $N_{STR}$ calculated from the data cover several orders of magnitude and were used to segment all Phase 4 data into two equal groups for high and low $N_{STR}$. Data are analyzed on this basis in a later section.

### Refiltration Parameter E and $C_o$

Data are analyzed in a later section for segmenting data for values of E less than or equal to and greater than 1.65, and for $C_o$ less than or equal to and greater than 18 mg/ℓ. These values were selected to divide the 38 data where refiltration data were obtained in Phase 4 into two equal segments. The distribution of data for each of the plants in the various groups is shown in Table 27.

## DEVELOPMENT OF OPERATIONAL MATHEMATICAL MODELS

Data for Phases 2, 3, and 4 were analyzed using the three models shown in Equations 18, 19, and 20 using multiple regressions and log transformations. A viscosity term was not added to the models because data collection covered a short time frame where variations were insignificant. Selected models including suspension properties were then tested using their own data.

### Regression Coefficients for Filter Media Depth and Grain Size

The effect of filter media depth and media grain size on performance was tested for all Phase 4 data using an equation of the form:

$$C = a\ C_o^b\ Q^c\ E^d\ L^e\ d_e^f \tag{28}$$

The values obtained for e and f were -0.30 and 0.34 with significance levels 0.15 and 0.07, respectively. Although significance levels are low, inclusion of L and $d_e$ did not result in a significant improvement in correlations. This factor, along with results in Phase 1, precluded further use of these variables in model development, except for testing of possible relationships between suspended particle and filter media grain sizes.

### Power Function Relationships for Particle Size and Grain Size

Power function relationships for forms of the filter coefficient were determined using all Phase 4 data for comparison with published data. Results are shown in Table 28. Exponents of less than -0.1 were obtained for Q as compared to values of -0.67 to -1 reported by FitzPatrick (1972), and shown in Table 8. Exponents for particle size were less than 0.1 and have low significance. An exponent of 2 for particle size is reported for classical interception and gravity theories (FitzPatrick, 1972) and was obtained for separate analysis of the Des Plaines River data. The exponent for $d_{50}$ has the opposite sign, also based on these theories and the exponent for $d_{nm}/d_{50}$ has a high significance level.

From analysis of individual plant data, it is clear that particle size

Table 27. Segmented data for high and low $N_{STR}$, $C_o$ and E.

| | | No. of Segmented Data | | | | | |
|---|---|---|---|---|---|---|---|
| | No. of Data | $N_{STR}$ | | $C_o$ | | E | |
| | | Low | High | Low | High | Low | High |
| Addison North | 6 | 2 | 4 | 4 | 2 | 1 | 5 |
| Addison S.-#2 | 4 | 2 | 2 | 0 | 4 | 0 | 4 |
| Addison S.-#4-7 | 18 | 11 | 7 | 0 | 18 | 0 | 18 |
| Barrington | 7 | 3 | 4 | 5 | 2 | 4 | 3 |
| Des Plaines R. | 6 | 2 | 4 | 1 | 5 | 3 | 3 |
| Lake Zurich | 9 | 6 | 3 | 7 | 2 | 9 | 0 |
| Lisle | 6 | 6 | 0 | 6 | 0 | 6 | 0 |
| Marionbrook | 5 | 0 | 5 | 0 | 5 | 5 | 0 |
| Romeoville | 5 | 1 | 4 | 4 | 1 | 4 | 1 |
| Total | 66 | 33 | 33 | 27 | 39 | 32 | 34 |

Table 28. Regression coefficients for Log $\frac{C}{C_o} = f(Q, C_o, E, d_{50}, d_{nm}, d_{nm}/d_{50})$ - Phase 4.

| | $r_t$ | a | b | c | d | e | f | g |
|---|---|---|---|---|---|---|---|---|
| **Log $C/C_o = a\ Q^c\ E^d\ d_{nm}^{\ e}$** | | | | | | | | |
| | .68 | -.17 | - | -.058 | 2.55 | .031 | - | - |
| (Signif.) | | | | (.20) | (0) | (.77) | | |
| **Log $C/C_o = a\ C_o^{\ b} Q^c\ E^d\ d_{nm}^{\ e}$** | | | | | | | | |
| | .68 | -.17 | -.014 | -.058 | 2.60 | .024 | | |
| (Signif.) | | | (.87) | (.21) | (0) | (.83) | - | - |
| **Log $C/C_o = a\ Q^c\ E^d\ d_{nm}^{\ e}\ d_{50}^{\ f}$** | | | | | | | | |
| | .70 | -.15 | - | -.097 | 2.22 | .098 | .19 | - |
| (Signif.) | | | | (.05) | (0) | (.37) | (.08) | |
| **Log $C/C_o = a\ C_o^{\ b} Q^c\ E^d d_{nm}^{\ e}\ d_{50}^{\ f}$** | | | | | | | | |
| | .70 | -.16 | -.032 | -.097 | 2.31 | .085 | .19 | - |
| (Signif.) | | | (.71) | (.06) | (0) | (.46) | (.07) | |
| **Log $C/C_o = a\ Q^c\ E^d (d_{nm}/d_{50})^g$** | | | | | | | | |
| | .68 | -.20 | - | -.074 | 2.50 | - | - | -.048 |
| (Signif.) | | | | (.13) | (0) | | | (.44) |

has an effect on filter performance. A weak dependence occurs for analysis of data between plants. Apparently the effect of particle size on filter performance may be negated by variables with stronger dependencies for analysis of all Phase 4 data. In addition, the particle size distributions vary widely between plants, as shown in Figures 44 to 48 , where individual plant data exhibit log normal, bimodal, and random distributions. Thus, a single parameter such as $d_{nm}$ may not adequately characterize the suspension for comparisons between plants.

### Development of Models for $C = f(C_o, Q)$ and $C = f(C_o, Q, E)$

The method discussed in Chapter VIII, where regression coefficients and the slopes and intercepts of plots of calculated vs. measured C are determined, was used to evaluate models for individual plant data and for groupings of data. If a model adequately describes the filtration process, then the intercept of the line of best fit of the plot of calculated vs. measured C should be close to zero and the slope close to one. Slopes less than about 0.6 generally indicate a poor fit of the model. Regression coefficients and slopes and intercepts for the plots of calculated vs. measured C are given in Table 29. Except for variable flow plants, the coefficient for Q was fixed at 0.26, the value obtained for the Addison South Phase 4 data.

For Hsiung's data, the straining model fits the data much better than the in-depth model with a slope of 0.89. The magnitude of the correlation coefficients for Hsiung's data is greatly influenced by two data points at 56 and 64 mg/ℓ, which leads to some question as to the validity of the model. It will be shown later that the model for straining has high validity since it predicts performance adequately for some of the Phase 4 straining data and some of the Phase 4 models provide a good fit for the two data points.

For the Addison South Phase 2 data, the slopes are less than 0.5 and no significant improvement occurs for inclusion of E in the correlation. During Phase 2, $C_o$ was very high and averaged 143 mg/ℓ. At the high solids levels, it is unlikely that the filter media was adequately cleaned during backwashing and solids breakthrough probably occurred. This may be the reason for the relatively poor correlation and weak dependence on E. The Phase 3 data in Table 29 show a strong correlation for the in-depth filtration model and a slight improvement when E is included although the slope is low. As discussed in Chapter IX, in-depth filtration is considered to be the dominant mode for these data.

For the Addison South Phase 4 data, no improvement in correlation is apparent for inclusion of E in the model although the regression coefficient for E is very high (-10.6). For the straining model, the significance levels for the coefficients for $C_o$ and Q are 0.60 and 0.47, respectively. These results are caused by the very strong correlation between $C_o$ and E, shown in Figure 56. Thus it does not matter which of the variables $C_o$ and E is included in the model. The validity of the straining model is discussed later.

The straining model for Addison North, Des Plaines River, and Romeoville shows a very strong correlation with a slope of 0.83. A very poor correlation with r of 0.10 and slope of 0.07 is obtained for the in-depth filtration model

Table 29. Regression coefficients for models and intercepts and slope for plots of calculated vs. measured C.

| Model | $C = a\,C_o^b Q^c$ | | | | | | $C = a\,C_o^b Q^c E^d$ | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Data Set(s) | r** | Intercept | Slope | a | b | c | r | Intercept | Slope | a | b | c | d |
| Hsiung's Data | .52 | 19 | .21 | 1.12 | .61 | * | .92 | 2.6 | .89 | .57 | 1.34 | * | -4.14 |
| AV 2 | .65 | 16 | .44 | 4.05 | .37 | .39 | .65 | 16 | .47 | 4.57 | .43 | .38 | -.86 |
| AV 3 | .83 | 5.8 | .59 | 1.34 | .48 | .45 | .87 | 5.0 | .63 | 15.8 | .30 | .46 | -3.36 |
| Phase 4 | | | | | | | | | | | | | |
| All Data | .63 | 3.4 | .38 | .72 | .59 | * | .77 | 2.1 | .65 | 1.20 | 1.01 | * | -3.84 |
| AV 4 | .82 | 2.0 | .69 | .23 | .88 | .27 | .83 | 1.9 | .69 | 10.1 | 1.49 | .26 | -10.6 |
| AN,DP,RO | .10 | 3.9 | .07 | .49 | .71 | * | .85 | .8 | .83 | 4.24 | 1.40 | * | -8.28 |
| BA,LZ,LI,MB | .78 | 2.8 | .55 | .47 | .78 | * | .79 | 2.7 | .57 | .82 | 1.06 | * | -3.47 |
| LZ,LI,MB | .90 | 2.2 | .69 | .80 | .65 | .32 | .92 | 2.0 | .75 | .66 | .54 | .28 | 1.57 |
| LOW $N_{str}$ | .41 | 4.8 | .13 | 2.57 | .19 | * | .47 | 3.9 | .31 | 3.05 | .33 | * | -1.29 |
| HIGH $N_{str}$ | .71 | 2.3 | .71 | .24 | .93 | * | .79 | .2 | 1.03 | .55 | 1.62 | * | -6.19 |
| LOW $C_o$ | .26 | 3.9 | -.05 | 1.46 | .27 | * | .56 | 1.0 | .34 | 2.62 | 1.16 | * | -8.02 |
| HIGH $C_o$ | .61 | 5.9 | .36 | 1.39 | .44 | * | .74 | 3.8 | .69 | 2.37 | .89 | * | -4.06 |
| LOW E | .58 | -0.8 | .53 | .36 | .82 | * | .83 | .6 | .91 | .54 | 1.07 | * | -2.30 |
| HIGH E | .76 | 3.5 | .52 | .28 | .86 | * | .77 | 1.0 | .82 | .51 | 1.36 | * | -4.53 |

*Coefficient for Q fixed at 0.26.
**Bivariate correlation coefficient for plot

for these plants.

A good fit is apparent for the in-depth model for Lake Zurich, Lisle, and Marionbrook. The exponent for Q of 0.32 is nearly identical to the 0.34 value obtained for the Phase 1 Marionbrock dry weather flow model. The exponent for E in Table 29 is 1.57, the only positive value obtained. This is not surprising since the normalized data plot in Figure 77 show an increase for $\text{Log} \dfrac{C/C_o}{C_o^{.4}\ Q^{.26}}$ with increasing E for those individual plants. The Barrington plant data were grouped with these plant data.

For segmenting of the data, the best fits were obtained for the high $N_{STR}$ and high E models with slopes of 1.03 and 0.82, respectively. Very poor fits are apparent for the low $N_{STR}$ and low $C_o$ models. The regression coefficients are strikingly similar for Hsiung's data and for the high E data which cover different $C_o$ ranges:

| | a | $b(C_o)$ | d(E) | Range of C mg/ℓ |
|---|---|---|---|---|
| Hsiung | .57 | 1.34 | -4.14 | 10-64 |
| High E | .51 | 1.36 | -4.53 | 1-12 |

This result obtained for different ranges of C and $C_o$ greatly enhances the validity of both models since they can predict outside of the range in which they were developed.

## TESTING OF MODELS WITH OTHER DATA

Selected straining models developed from Phase 4 data were tested, using independent data. Statistics are given in Table 30. Plots of calculated vs. measured C are shown in the following figures for Hsiung's data:

| Figures | Models |
|---|---|
| 78 | High and low $N_{STR}$ |
| 79 | High and low E |
| 80 | AV4 and AN, DP, RO |

As discussed previously, the two data points for C of 56 and 64 mg/ℓ have a large effect on the correlations for Hsiung's data. The high $N_{STR}$ model overpredicts C for the two data points by 20 to 25 percent, as contrasted with the high E model which underpredicts by approximately the same amount and the AV4 and AN, DP, RO models which overpredict by about 10 to 45 percent. These results strengthen the validity of the two data points. The low $N_{STR}$ model provides a very poor fit. For other models, the lower C data show wide scatter with a tendency to overpredict for four of the data points. The other data points are relatively close to the line with a slope of one. The data point at a measured C of 12 mg/ℓ in Figure 80, where C is greatly

Table 30. Intercepts and slopes for plots of calculated vs. measured C for testing models with independent data.

| Data Set | Model | r* | Intercept mg/l | Slope |
|---|---|---|---|---|
| Hsiung | High $N_{str}$ | .93 | -6.8 | 1.24 |
| | Low $N_{str}$ | .91 | 7.1 | .07 |
| | High E | .93 | 1.0 | .72 |
| | Low E | .87 | 8.9 | .49 |
| | AV 4 | .72 | -7.6 | 1.24 |
| | AN, DP, RO | .82 | -5.6 | 1.12 |
| High E | Hsiung | .77 | 2.7 | .75 |
| AV 4 | | .84 | 1.4 | 1.01 |
| AN, DP, RO | | .67 | 1.7 | .49 |
| AV 4 | AN, DP, RO | .83 | 1.9 | .79 |
| AN, DP, RO | AV 4 | .81 | 0.2 | 1.01 |

*Bivariate correlation coefficient for plot.

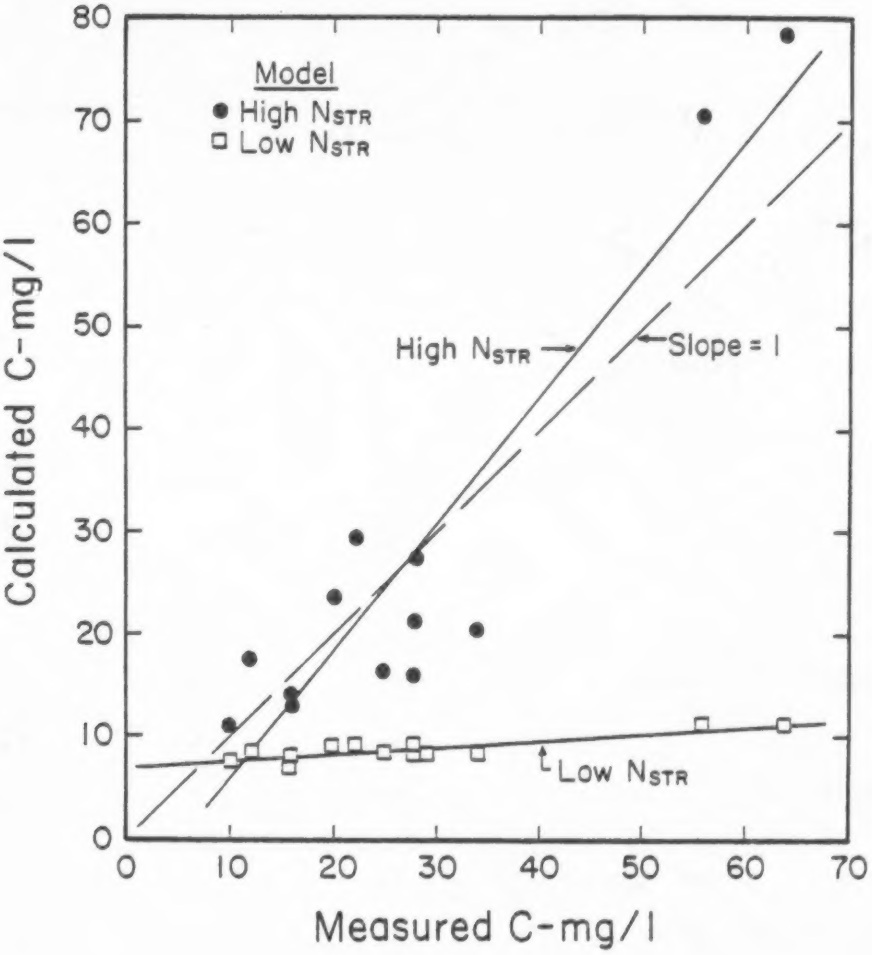


Figure 78. Calculated vs. measured C, models for high and low $N_{STR}$, Hsiung's data.

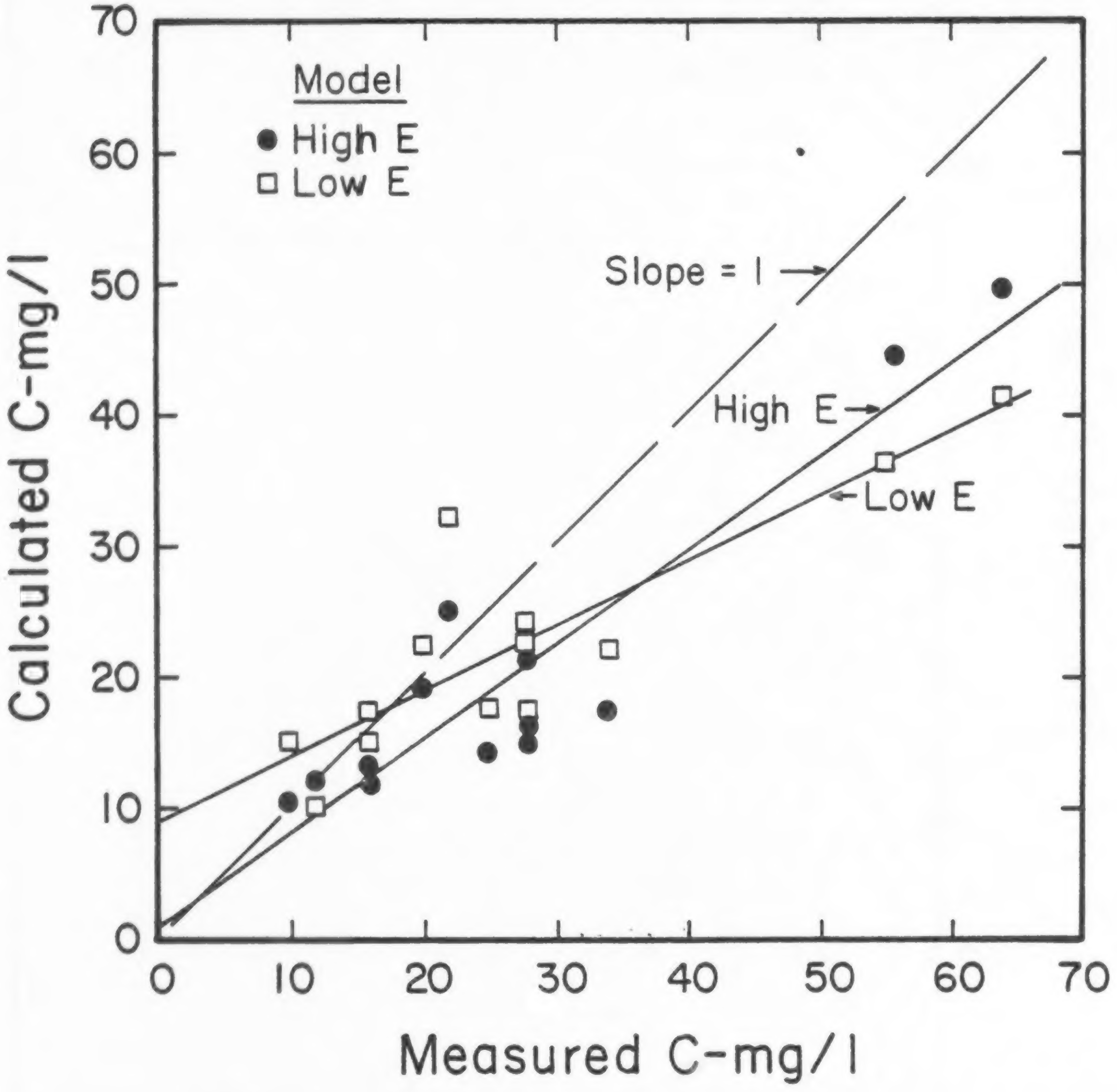


Figure 79. Calculated vs. measured C, models for high and low E, Hsiung's data.

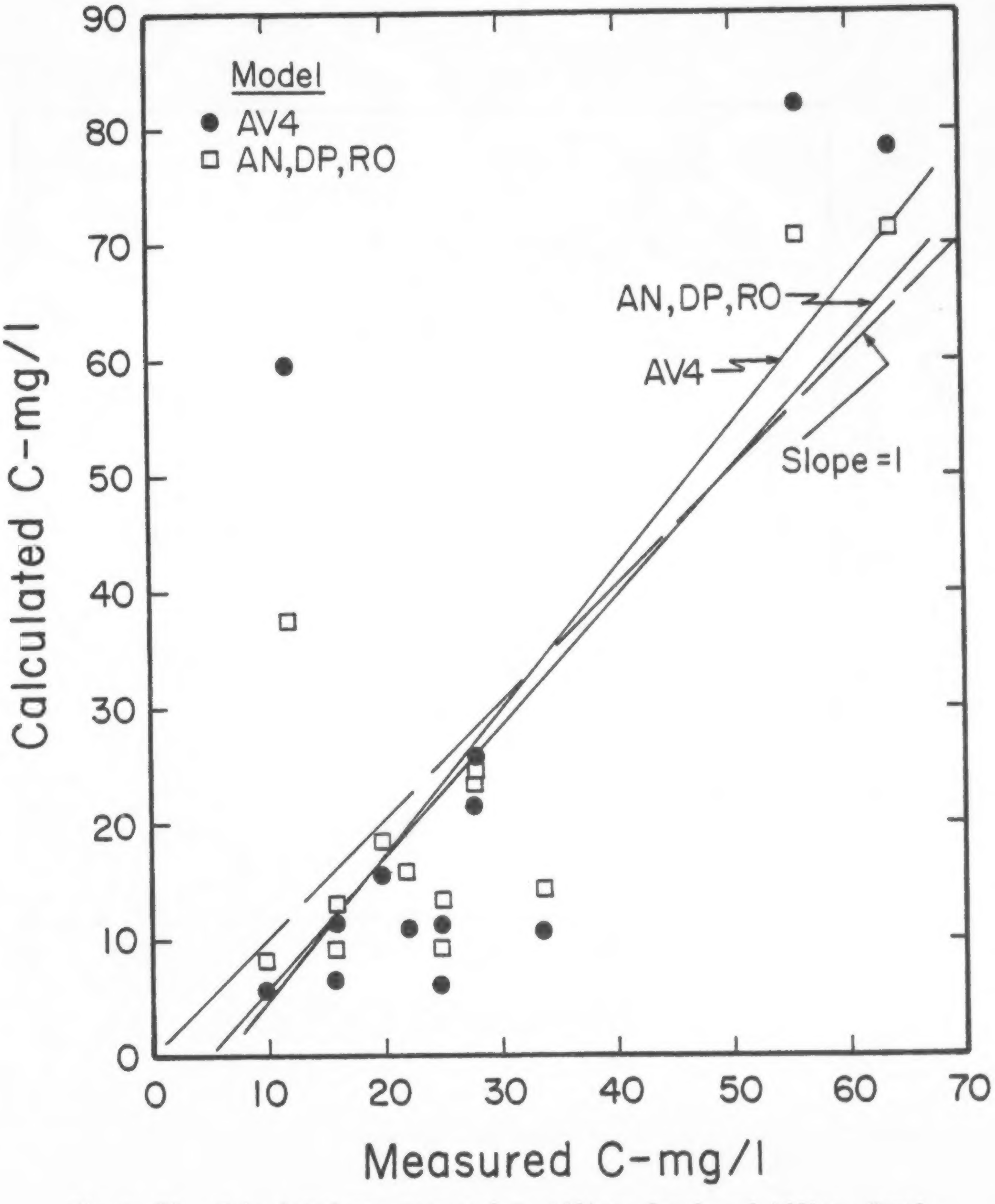


Figure 80. Calculated vs. measured C, Addison South and Addison North, Des Plaines River, and Romeoville Models, Hsiung's data.

overpredicted, results from a very low value of E and the high negative coefficients for E in the AV4 and AN, DP, RO models.

The straining model developed from Hsiung's data was tested using selected data from Phase 4. A plot of calculated vs. measured C is shown in Figure 81 for the high E data. Except for the Addison South data, a good fit is apparent. Three of the AS data points at a measured C of 5 to 7 mg/$\ell$, where C is overpredicted, are for Filter No. 2. The Filter No. 2 data were not used in development of the AV4 model because only four data were obtained and may be suspect because of malfunctions in the air scour system. C is predicted within ± 50 percent for about 75 percent of the data in Figure 81.

The plot for the AV4, AN, DP, and RO data for the model obtained from Hsiung's data is shown in Figure 82 . The line of best fit for the AV4 data has a slope of 1.0 but overpredicts C slightly. A better prediction is obtained for most of the AN, DP, and RO data. For all four plants, C is predicted within ± 30 and 40 percent for about 70 and 80 percent of the data, respectively.

The AN, BA, DP model is tested using the AV4 data in Figure 83. The data are not as well correlated as in the plot for the AV4 model and AN, DP, RO data shown in Figure 84. If the data points for $E \leq 1.65$ are excluded, a near perfect fit of the data is obtained in Figure 84. The Addison North data point that falls on the line with slope of one has an E of 1.64. In Figure 84, C is predicted within ± 30 percent for about 80 percent of the data. The AV4 model gives an excellent fit for the data with an intercept of 0.2 mg/$\ell$ and a slope of 1.0 for the line of best fit, although there are several outlying points. C is predicted within ± 20 percent for about 60 percent of the data and within ± 40 percent for 80 percent of the data.

The AV4 model provides an excellent fit for the AN, DP, RO data, even though the coefficients for $C_o$ and E have low significance, as discussed previously. The regression coefficients for E for the AV4 and AN, DP, RO models have high negative values of -10.6 and -8.28, respectively. The high value for the AV4 model may have resulted from the strong correlation between $C_o$ and E. The high negative coefficients may be the reason why some of the calculated C data in Figure 80, for testing with Hsiung's data, are low.

## MODEL SELECTION AND APPLICATION

The validity and utility of a model is greatly enhanced if it can adequately predict outside the range of data from which it was developed. Two of the models developed from Phase 4 data for C less than 12 mg/$\ell$ were able to predict performance at C = 56 and 64 mg/$\ell$ with ± 20 to 25 percent. Testing of the model obtained from Hsiung's data with high C gave predictions within ± 30 percent for 70 percent of the data where straining was considered to be the dominant particle collection mode.

As in Phase 1, filter media size and depth did not correlate with filter performance. The AV, DP and RO plants represent the extremes in media size and depth encountered in the study. The fact that the data from these plants correlate well further supports the conclusion from Phase 1 that filter per-

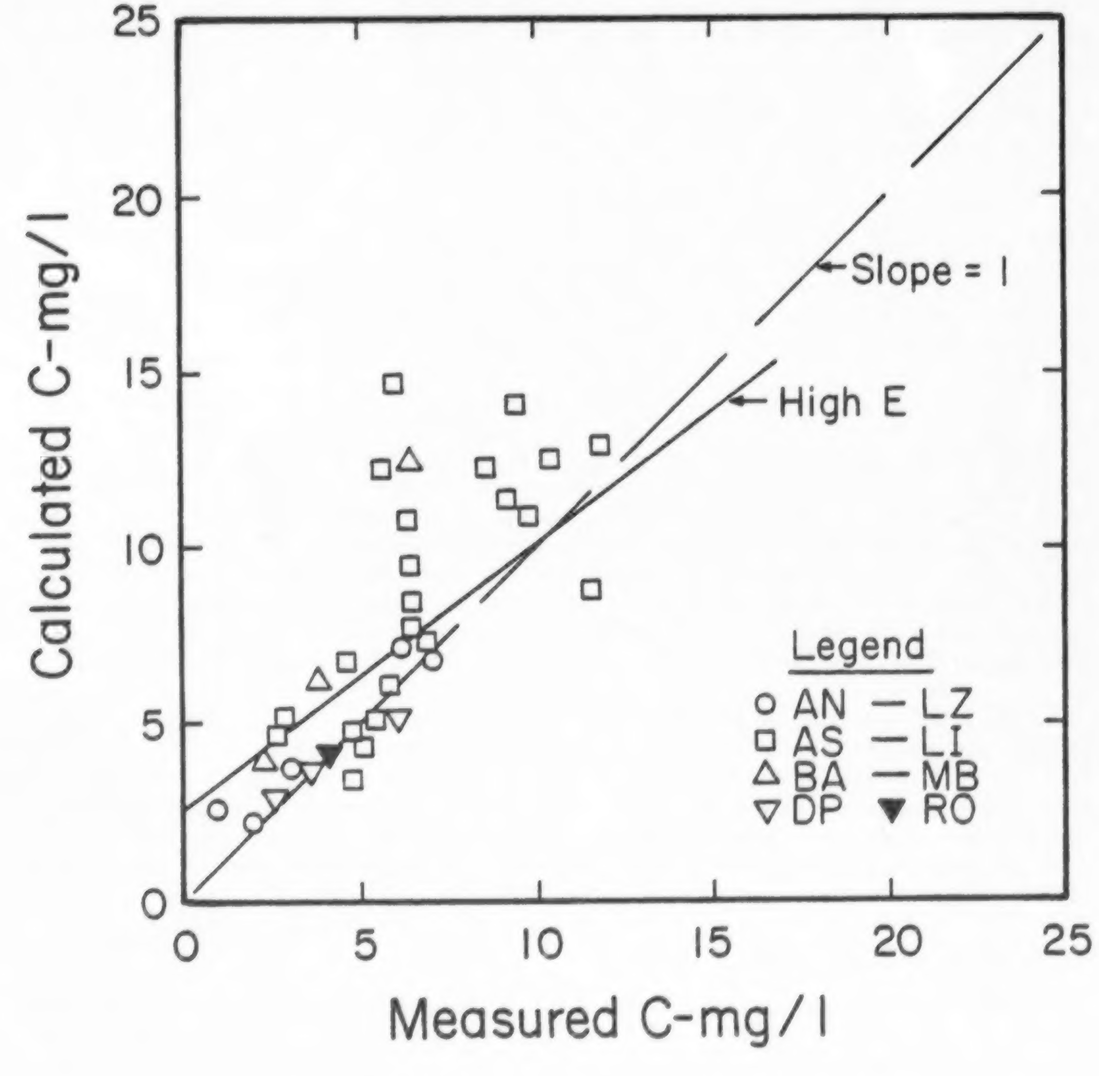


Figure 81. Calculated vs. measured C, model for Hsiung's data, high E data.

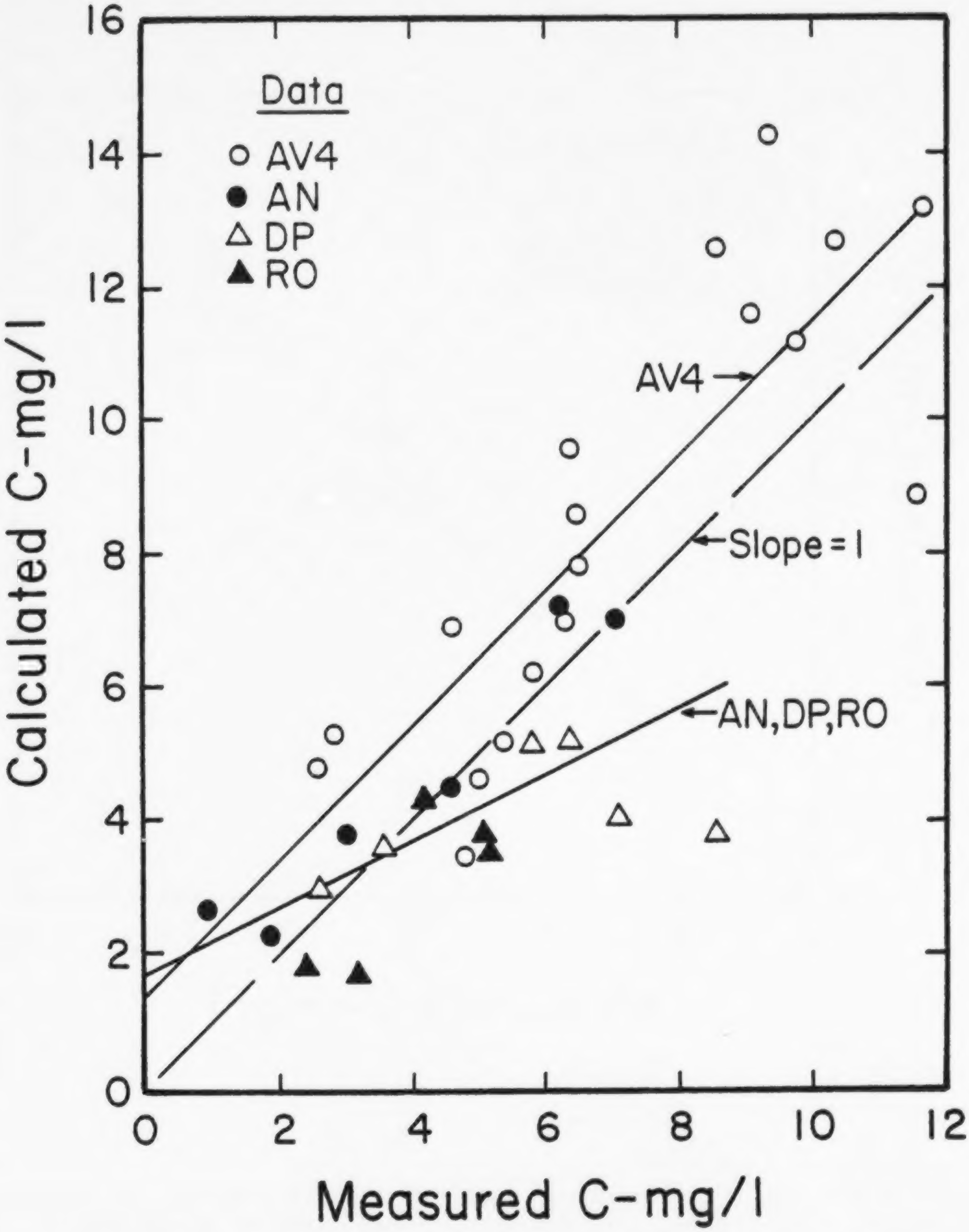


Figure 82. Calculated vs. measured C, model for Hsiung's data, Addison South, Addison North, Des Plaines River, and Romeoville data.

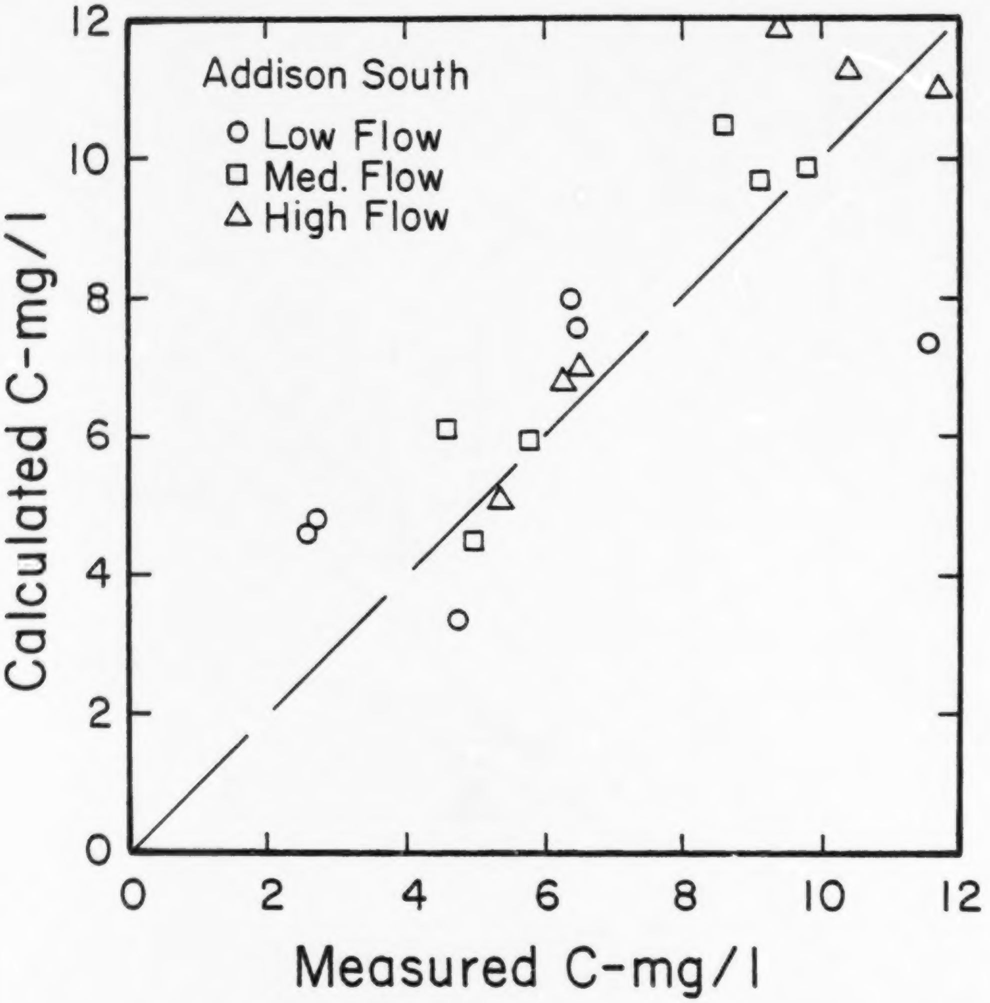


Figure 83. Calculated vs. measured C, Addison North, Des Plaines River, and Romeoville model, Addison South data.

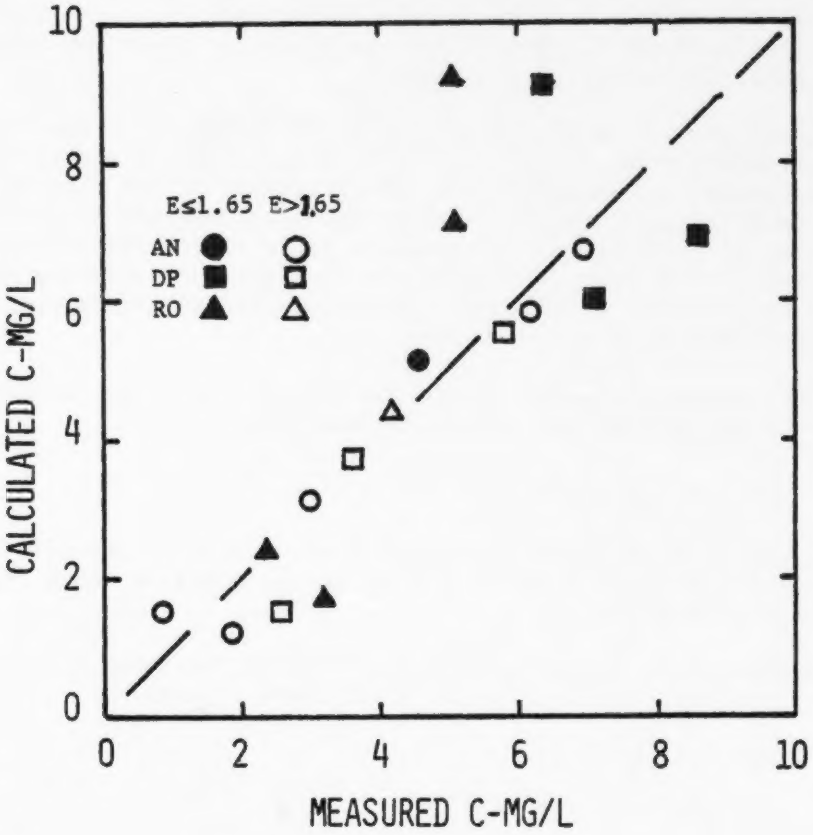


Figure 84. Calculated vs. measured C, Addison South straining model, Addison North, Des Plaines River, and Romeoville data.

formance is relatively independent of media size and depth over the ranges encountered in this study.

In order to develop empirical models of filter performance, it is necessary to vary the flow to individual filters receiving the same influent suspension. In flow variation tests, filter performance varied as a function of flow to the 0.27 to 0.45 power if refiltration parameters were not included. With inclusion of the parameter E, the regression coefficient for flow was 0.26 for one plant as compared to 0.34 for the Marionbrook in-depth filtration model developed in Phase 1. The difference in $Q^c$ for these two exponents is relatively small (5 percent at 2 gpm/sf).

For plants where in-depth filtration was believed to be the dominant particle collection mode, inclusion of E in models did not result in a significant improvement in correlations. Prediction of filter performance can be greatly improved using empirical refiltration parameters as opposed to solids loading if straining is the dominant particle collection mode. In testing of models with data from other plants, both the straining and in-depth models tend to overpredict effluent suspended solids if the other particle collection mode dominates for most data.

From this study, the model considered to best represent in-depth filtration is the Marionbrook dry weather flow model:

$$C = 0.40\ C_o^{.86}\ Q^{.34} \qquad (22)$$

The Marionbrook model is considered to be best because it provided the best fit for Phase 1 data and for data in later phases where in-depth filtration was considered to dominate.

For straining the choice is between the model developed from high E data, the AN, DP, RO model, and the Addison South Phase 4 model:

High E (> 1.65)

$$C = .51\ C_o^{1.36}\ Q^{.26}\ E^{-4.53} \qquad (29)$$

AN, DP, RO

$$C = 4.24\ C_o^{1.40}\ Q^{.26}\ E^{-8.28} \qquad (30)$$

AV4

$$C = 10.1\ C_o^{1.49}\ Q^{.26}\ E^{-10.6} \qquad (31)$$

The model for the high E data has a much lower negative exponent for E than the values of 10.6 and 8.28 obtained for the Addison South and AN, DP, RO Phase 4 data. A lower negative exponent may be more desirable because the model would tend to overpredict C less if in-depth filtration is the dominant particle collection mode. However, the model for high E data tends to overpredict C for the Addison South data.

The high E model provides the best fit for Hsiung's data and has nearly the same constant and exponents. However, the near perfect fit obtained in Figure 84 for the AV4 model tested with AN, DP, RO data, if the data for $E \leq 1.65$ are excluded, strongly favors its use for high E values. Since the AN, RO, DP model has a lower negative exponent for E, it is the model of choice for high E.

A method does not now exist to determine a priori which particle collection mode will be dominant over a range of operating conditions. Even so, it is believed that these models can now be applied with caution in predicting filter performance. For plants that have tertiary ponds ahead of the filters, the in-depth model can be applied since particle size and E will likely be small, as shown for the Lake Zurich, Lisle, and Marionbrook plants. In any event, particle size and refiltration tests should be conducted before the model is applied.

For sand filters, the nearly perfect fit for high E strongly suggests that the AN, DP, RO model can be applied directly (c.f., Figure 84). Until further work is done, the model should not be used for suspensions with low E. In the interim, the Marionbrook model should be used for low E data. It provided a relatively good fit for the sand filtration data reported by EPA (1975) (c.f., Figure 43).

For dual media filters, the situation is not as clear since the AN, DP, RO model tested with the Addison South data does not provide a significant improvement over an in-depth filtration model for Addison South tested with its own data. As discussed previously, this may be caused by the high correlation between $C_0$ and E. A further uncertainty is that the Barrington data does not correlate well with the AN, DP, RO model, as shown below for $E \geq 1.65$.

| Calculated C mg/ℓ | Measured C mg/ℓ |
|---|---|
| 11.4 | 6.5 |
| 6.2 | 3.8 |
| 3.8 | 3.0 |

For dual media filters, it is believed that the model should not be used unless $d_{nm}$ and E are greater than about 15 μm and 1.7, respectively.

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# APPENDIX A

## BIVARIATE CORRELATION COEFFICIENTS

Table A-1. Bivariate correlation coefficients for secondary plant operating data and $C_o$, C, and $C/C_o$ - Phase 1 - variable flow plants.

| Secondary Plant Variable | No. of Data | Mean | r– $C_o$ | r - C Low Q | r - C Med. Q | r - C High Q | r - $C/C_o$ Low Q | r - $C/C_o$ Med. Q | r - $C/C_o$ High Q |
|---|---|---|---|---|---|---|---|---|---|
| **Addison South** | | | | | | | | | |
| F/M | 17 | .11 | -.20 | -.47 | -.37 | -.36 | -.43 | -.35 | -.34 |
| Rear. SS-mg/ℓ | 35 | 6900 | .22 | .59 | -.22 | .30 | .47 | .09 | .28 |
| Contact SS-mg/ℓ | 35 | 4600 | -.11 | .63 | .10 | .16 | .58 | .19 | .27 |
| SVI-mℓ/mg | 35 | 70 | -.26 | .51 | -.30 | -.07 | .46 | -.11 | -.02 |
| D.O.- mg/ℓ | 35 | 0.9 | .44 | -.23 | .38 | .43 | -.38 | .10 | .18 |
| **Lake Zurich** | | | | | | | | | |
| F/M | 5 | .03 | - | - | - | - | - | - | - |
| Reaer. SS-mg/ℓ | 8 | 3600 | - | - | - | - | - | - | - |
| Contact SS-mg/ℓ | 12 | 2700 | .17 | - | .61 | - | - | .03 | - |
| SVI-mℓ/mg | 12 | 100 | -.24 | - | -.36 | - | - | -.02 | - |
| D.O.-mℓ/ℓ | 31 | 2.4 | -.22 | .51 | -.10 | - | - | .22 | - |
| **Lisle** | | | | | | | | | |
| F/M | 12 | .12 | .23 | .56 | .42 | .75 | .30 | .24 | .43 |
| Reaer. SS-mg/ℓ | 12 | 5700 | .01 | .16 | .62 | .34 | -.14 | .46 | .08 |
| Contact SS-mg/ℓ | 12 | 4800 | -.03 | .09 | .29 | .08 | .10 | .27 | .19 |
| SVI-mℓ/mg | 12 | 140 | -.04 | .28 | -.05 | .10 | .21 | -.04 | .10 |
| D.O.-mg/ℓ | 12 | 1.0 | .57 | -.21 | -.10 | -.19 | -.19 | -.41 | -.42 |
| **Marionbrook** | | | | | | | | | |
| F/M | 34 | .10 | .21 | -.31 | -.26 | -.21 | .24 | -.45 | -.63 |
| Rear. SS-mg/ℓ | 34 | 5200 | -.08 | .28 | .21 | .31 | .12 | .22 | .22 |
| Contact SS-mg/ℓ | 34 | 4100 | .08 | .47 | .38 | .24 | .16 | .28 | -.06 |
| SVI-mℓ/mg | 34 | 130 | .06 | .52 | .29 | -.19 | .13 | .09 | .42 |
| D.O.-mg/ℓ | 31 | 1.1 | .12 | -.26 | -.31 | .08 | -.02 | -.26 | -.55 |

Table A-2. Bivariate correlation coefficients for secondary plant operating data and $C_o$, C, and $C/C_o$ - Phase 1 - non-variable flow plants.

| Secondary Plant Variable | No. of Data | Addison North |  |  |  | No. of Data | Addison South (75) |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  |  | Mean | r |  |  |  | Mean | r |  |  |
|  |  |  | $C_o$ | C | $C/C_o$ |  |  | $C_o$ | C | $C/C_o$ |
| F/M | 20 | .018 | .08 | -.23 | -.19 | 18 | .091 | .18 | -.44 | -.42 |
| Reaer.SS-mg/ℓ | 52 | 8300 | .39 | -.17 | -.41 | 48 | 6100 | .03 | .20 | .02 |
| Contact SS-mg/ℓ | 52 | 4400 | .52 | .09 | -.32 | 48 | 4200 | 0 | .24 | .11 |
| SVI-ml/mg | 52 | 170 | -.36 | .03 | .33 | 48 | 60 | -.11 | .06 | .07 |
| D.O.-mg/ℓ | 52 | 5.5 | .09 | .04 | -.02 | 48 | 3.0 | .17 | -.02 | -.16 |
|  |  | Barrington |  |  |  |  | Des Plaines River |  |  |  |
| F/M | 53 | .13 | -.58 | -.19 | .44 | 5 | .05 |  |  |  |
| Reaer.SS-mg/ℓ | 57 | 7800 | .02 | .21 | .15 | 8 | 6100 | (insufficient data) |  |  |
| Contact SS-mg/ℓ | 57 | 3100 | -.21 | -.03 | .11 | 8 | 3000 |  |  |  |
| SVI-ml/mg | 57 | 80 | -.28 | -.26 | -.11 | 0 | - |  |  |  |
| D.O-mg/ℓ | 0 | - | - | - | - | 32 | 3.8 | .34 | .43 | -.12 |
|  |  | Romeoville |  |  |  |  |  |  |  |  |
| F/M | 23 | .083 | -.08 | .01 | .19 |  |  |  |  |  |
| Reaer.SS-mg/ℓ | 25 | 4000 | -.16 | -.41 | -.16 |  |  |  |  |  |
| Contact SS-mg/ℓ | 25 | 2400 | -.16 | -.50 | -.39 |  |  |  |  |  |
| SVI-ml/mg | 25 | 270 | -.05 | -.40 | -.38 |  |  |  |  |  |
| D.O.-mg/ℓ | 0 | - | - | - | - |  |  |  |  |  |

Table A-3. Bivariate correlation coefficients for filter performance, particle size statistics, and refiltration parameters.

|  | Phase 3 C to: |  | Phase 4 C to: | Phase 3 $C_o$ to: |  | Phase 4 $C_o$ to: | Phase 3 $C/C_o$ to: |  | Phase 4 $C/C_o$ to: | Phase 3 R to: |  | Phase 4 R to: |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | AS | DP | All | AS | DP | All | AS | DP | All | AS | DP | All |
| No. of cases | 9 | 19 | 38 | 9 | 19 | 38 | 9 | 19 | 38 | 9 | 19 | 38 |
| $d_4m$ | -.37 | .10 | -.34 | -.07 | .11 | -.18 | -.28 | .11 | -.29 | -.35 | -.10 | .39 |
| dnm | -.48 | 0 | -.39 | -.13 | .33 | -.26 | -.40 | -.11 | -.25 | .13 | -.21 | .28 |
| dsm | -.46 | .04 | -.40 | -.06 | .32 | -.25 | -.41 | -.06 | -.29 | .32 | -.21 | .35 |
| dvm | -.41 | .08 | -.38 | -.06 | .22 | -.22 | -.34 | .03 | -.29 | .36 | -.17 | .38 |
| NT | .80 | .01 | .76 | .58 | .62 | .72 | .43 | -.37 | .06 | .03 | .56 | -.04 |
| $\sigma^2$ | -.38 | .08 | -.35 | -.02 | .29 | -.21 | -.35 | 0 | -.28 | .39 | -.22 | .38 |
| $\sigma/\bar{x}$ | -.37 | .16 | -.13 | .03 | -.15 | -.03 | -.38 | .23 | -.23 | .51 | .06 | .41 |
| %S1 | .47 | .10 | .26 | .31 | .21 | .29 | .27 | -.08 | -.01 | .18 | .02 | .05 |
| %S2 | -.32 | -.16 | -.19 | -.36 | -.56 | 0 | -.09 | .16 | .27 | -.34 | .21 | -.34 |
| %S3 | -.51 | .01 | .01 | -.27 | -.16 | -.15 | -.27 | .13 | .28 | -.23 | .01 | -.20 |
| %S4 | -.22 | .06 | -.43 | .25 | .50 | -.25 | -.40 | -.17 | -.33 | .50 | -.25 | .28 |

TABLE A-3 (cont'd.)

| | Phase 3 | | Phase 4 | Phase 3 | | Phase 4 |
|---|---|---|---|---|---|---|
| | G to: | | G to: | E to: | | E to: |
| | AS | DP | All | AS | DP | All |
| No. of cases | 9 | 19 | 38 | 9 | 19 | 38 |
| $d_4m$ | .17 | .10 | -.25 | .47 | .11 | .20 |
| dnm | .35 | .22 | -.19 | .47 | .19 | .14 |
| dam | .22 | .21 | -.24 | .50 | .17 | .17 |
| dmm | .18 | .16 | -.25 | .48 | .14 | .19 |
| NT | -.73 | -.41 | .22 | -.70 | -.19 | .14 |
| $\sigma^2$ | .12 | .22 | -.25 | .44 | .17 | .19 |
| $\sigma/\bar{x}$ | .05 | -.10 | -.28 | .47 | -.12 | .19 |
| % S1 | -.47 | -.05 | .04 | -.34 | -.07 | .06 |
| % S2 | .32 | -.17 | .06 | .07 | -.14 | -.23 |
| % S3 | .79 | .02 | .16 | .61 | .08 | -.14 |
| % S4 | -.20 | .23 | -.19 | .19 | .16 | .16 |

## APPENDIX B

## CALCULATION OF EQUIVALENT MEDIA DIAMETER

A modifed form of Kozeny's equation for flow through porous medium was used to calculate $d_e$, the equivalent media diameter to give the same headloss.

Kozeny Equation:

$$\frac{h}{L} = \frac{1}{Kg} \nu V \frac{(1 - \epsilon)^2}{\epsilon^3} \left(\frac{S}{d}\right)^2$$

where

$K$ = Kozeny constant

$h$ = headloss

$L$ = depth of bed

$\nu$ = kinematic viscosity

$\epsilon$ = porosity, approximately 0.4 for sand and 0.6 for anthracite

$S$ = shape factor, approximately 6.1 for sand and 7.4 for anthracite

$d$ = geometric mean grain diameter

$V$ = velocity of flow

Rearrangement of Kozeny's equation and including headloss components for sand and anthracite gives

$$\frac{hgK}{\nu V} = \frac{(1 - e_s)^2}{e_s^3} \left[\frac{S_s}{d_s}\right]^2 L_s + \frac{(1 - e_a)^2}{e_a^3} \left[\frac{S_a}{d_a}\right]^2 L_a = A$$

where subscripts denote sand and anthracite media. This equation reduces to

$$209 \frac{L_s}{d_s^2} + 40.6 \frac{L_a}{d_a^2} = A$$

The sum $209\ L_s + 40.6\ L_a$ was determined and $d_e$ defined as

$$d_e = \left[ \frac{209\ L_s + 40.6\ L_a}{209 \frac{L_s}{d_s^2} + 40.6 \frac{L_a}{d_a^2}} \right]^{1/2}$$

# APPENDIX C

## UNITS FOR REFILTRATION AND STRAINING PARAMETERS

### Units for E

$$E = (R^{1/3}\ G)^{1/2} = R^{1/6}\ G^{1/2}$$

From Chapter VI: $R = AL_t\rho$ and $G = (\frac{K''}{L_t S^2})^{1/2}$

From Equation 11, K' has the same units as

$$L_t^{1/3}\ S^{2/3}\ (\frac{V}{t})^{1/3} \quad \text{or}$$

$$L^{1/3}\ (\frac{L^2}{L^3})^{2/3}\ (\frac{L^3}{T})^{1/3} = (\frac{L^2}{T})^{1/3}$$, where L and T are length and time, respectively.

$G = (\frac{K''}{L_t S^2})^{1/3}$ , $K'' = (K')^3$ so units are $\frac{L^2}{T}$

Units for G: $\left(\frac{L^2}{TL\left(\frac{L^2}{L^3}\right)^2}\right)^{1/3} = (\frac{L^3}{T})^{1/3} = \frac{L}{T^{1/3}}$

Units for R = Mass (M)

Units for E

$$\left(M^{1/3}\ \frac{L}{T^{1/3}}\right)^{1/2} = (\frac{ML^3}{T})^{1/6}$$

Then E should appear in a grouping to the 6th power for mass to cancel out evenly. Other variables that should be considered are $C_o$, Q, $d_{nm}$, $d_{10}$, and μ. For mass to cancel μ must be squared in the denominator. If one considers the grouping $\frac{C_o\ Q\ E^6}{\mu^2}$ the units are

$$\frac{\frac{M}{L^3}\ \frac{L}{T}\ \frac{ML^3}{T}}{\frac{M^2}{L^2T^2}} = L^3$$

and $d_{nm}$ and $d_{10}$ would have different exponents by 3 for the grouping to be dimensionless. Suspended particle size would be expected to have a much stronger influence on straining than media diameter for the range encountered in this study and should therefore have a larger exponent than media size and be in the numerator.

Thus, if an exponent of 4 was selected for $d_{nm}$, an exponent of 7 would be needed for $d_{10}$. For this reason, an arbitrary dimensional grouping, dimensionless except for L, was selected to represent straining:

$$N_{STR} = \frac{C_o\ Q\ E^6\ d_{nm}^4}{\mu^2\ d_{10}^2}$$

The group has units $L^5$.

# APPENDIX D

## SURVEY OF U.S. TERTIARY FILTERS

Prior to the conduct of this award (EPA Grant R803212), a survey of existing and planned municipal tertiary filters in the U.S. was conducted. Lists of tertiary filter locations and operating data were requested from the 50 states' water pollution control administrators in September 1973 and are believed current as of June, 1974.

Five states did not respond and nineteen states had no tertiary filters following municipal effluents at that time.

The following summary of tertiary filters in fourteen states comprised all tertiary filters in existence at that time except for small biological treatment package plants (these were quite numerous). A more detailed summary of the 50 states response is given on Table D-1.

| State | Number of filters | Operating information available* |
|---|---|---|
| Alaska | 2 | |
| California | 7 | x |
| Colorado | 4 | |
| Illinois | 25 | x |
| Indiana | 2 | |
| Maryland | 2 | x |
| Michigan | 7 | x |
| Minnesota | 5 | |
| Mississippi | 2 | |
| New Jersey | 7 | |
| New Mexico | 2 | |
| New York | 3 | |
| Oregon | 4 | |
| Texas | 5 | x |

*design or operating information including suspended solids and BOD have been received by us or are available in the literature.

Table D-1.

| State | Date | Operating | Planned or Constructed | Addresses or Location | Comments (See Key) Flow (1) Performance (2) Design (3) |
|---|---|---|---|---|---|
| Alabama | 9/6/73 | None | | | |
| Alaska | 9/6/73 | 2(?) | | x | |
| Arizona | 9/6/73 | 2(pp) | 5(pp) | x | |
| Arkansas | No Response | | | | |
| California | 9/19/73 | 6, 3(pp) | Many | x | (1) (3) |
| Colorado | 9/6/73 | 5(?) | 4 (1974) (?) | x | |
| Connecticut | 8/16/74 | 17? | | x | (2) (3) |
| Delaware | 9/18/73 | 5(pp) | | x | (1) |
| Wash. D.C. | 9/7/73 | None | | | |
| Florida | 8/14/73 | | | | too much work to get info |
| Georgia | 6/5/74 | 36(pp) | | x | |
| Hawaii | 9/19/73 | None | | | |
| Idaho | 9/5/73 | None | | | |
| Illinois | 10/15/73 | 30 | 25 | x | (1) (2) (3) |
| Indiana | 9/26/73 | 2(?) | | x | |
| Iowa | 9/7/73 | None | | | |
| Kansas | 9/14/73 | None | | | |
| Kentucky | 11/6/73 | | | | no answer |
| Louisiana | 10/3/73 | None | | | |
| Maine | 8/7/73 | None | 2(?) | x | |
| Maryland | 11/19/73 | 1(pp) | 1 | x | (1) (2) (3) |
| Massachusetts | 1/1/71 | 8 | | x | (1) (3) |
| Michigan | 8/13/73 | 11(?) | 3(?) | x | (3) |
| Minnesota | 9/20/73 | 5(?) | | x | |
| Mississippi | 9/6/73 | some(pp) | | x | |
| Missouri | 9/4/73 | None | | | |
| Montana | 9/17/73 | None | | | |
| Nebraska | 9/5/73 | None | | | |

Table D-1 (Continued)

| State | Date | Operating | Planned or Constructed | Addresses or Location | Comments<br>Flow (1)<br>Performance (2)<br>Design (3) |
|---|---|---|---|---|---|
| Nevada | 9/11/73 | None | | | |
| New Hampshire | 10/2/73 | Few(pp) | | | |
| New Jersey | 12/28/73 | 2,5(pp) | | x | (1) (3) |
| New Mexico | 9/4/73 | 3(pp) | 4(?) | x | |
| New York | 3/29/73 | 46(?)<br>3 rapid(?) | | | |
| N. Carolina | 10/1/73 | | | | no answer |
| N. Dakota | 9/5/73 | | | | |
| Ohio | No response | | | | |
| Oklahoma | 9/18/73 | 1(pp) | | x | no answer |
| Oregon | 9/26/73 | 4, 5(pp) | | x | (1) |
| Pennsylvania | 11/16/73 | 49(?) | | x | may all be intermittent sand filters<br>some (1) (3) |
| Rhode Island | 9/6/73 | 8(pp) | | x | (1) (3) |
| S. Carolina | No response | | | | |
| S. Dakota | 9/4/73 | | | | |
| Tennessee | 11/6/73 | 24(pp) | 4(pp) | x | (3) some |
| Texas | 9/26/73 | 3(?), 2(pp) | | x | |
| Utah | 9/17/73 | | 2 | | |
| Vermont | 1/29/74 | 15(pp) | | | |
| Virginia | No response | | | | |
| Washington | 11/7/73 | None | | | |
| W. Virginia | 6/21/74 | None | | | |
| Wisconsin | 9/24/73 | 1(pp) | | x | |
| Wyoming | 9/4/73 | None | | | |

Key

number (pp) - gives number of package plant or small facilities < 300,000 gpd

number (?) - unable to determine whether are small package plants or not

flow (1) - average or design daily average or both flows given

design (3) - type of preceeding process and perhaps information on whether multimedia, single media, intermittent

performance (2) - qualitative or semiquantitative performance information given

no response - no response received from first letter (contact)

no answer - no response received from suggested contact